GENETIC VARIATION IN WOOD BASIC DENSITY AND MOE AND THEIR RELATIONSHIP WITH GROWTH TRAITS IN TEAK (*TECTONA GRANDIS* L. F.) GROWN IN SEED ORCHARDS OF KERALA

By

JILJITH, K.P.

THESIS

Submitted in partial fulfillment of the requirement for the degree

Master of Science in Forestry

Faculty of Forestry

Kerala Agricultural University

DEPARTMENT OF WOOD SCIENCE

COLLEGE OF FORESTRY

KERALA AGRICULTURAL UNIVERSITY

VELLANIKKARA, THRISSUR -680 656

KERALA, INDIA

2016

DECLARATION

I hereby declare that this thesis entitled "**Genetic variation in wood basic density and MOE and their relationship with growth traits in teak (*Tectona grandis* L. f.) grown in seed orchards of Kerala**" is a bona fide record of research done by me during the course of research and that the thesis has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title, of any other University or Society.

Vellanikkara — JILJITH, K.P.

Date: — (2012-17-103)

Dr. E.V. Anoop — Date:

Associate Professor and Head,
Dept. of Wood Science,
College of Forestry
Kerala Agricultural University
Vellanikkara, Thrissur, Kerala

Dr. E.V. Anoop

Associate Professor and Head,
Dept. of Wood Science,
College of Forestry
Kerala Agricultural University
Vellanikkara, Thrissur, Kerala

Dated:

CERTIFICATE

Certified that this thesis, entitled **“Genetic variation in wood basic density and MOE and their relationship with growth traits in teak (*Tectona grandis* L. f.) grown in seed orchards of Kerala”** is a record of research work done independently by **Mr. Jiljith, K.P. (2012-17-103)** under my guidance and supervision and it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to him.

Dr. E.V. Anoop
Chairman
Advisory committee

CERTIFICATE

We, the undersigned members of advisory Committee of **Mr. Jiljith, K.P. (2012-17-103)** a candidate for the degree of **Master of Science in Forestry** agree that this thesis entitled **"Genetic variation in wood basic density and MOE and their relationship with growth traits in teak (*Tectona grandis* L. f.) grown in seed orchards of Kerala"** may be submitted by **Mr. Jiljith, K.P. (2012-17-103)**, in partial fulfilment of the requirement for the degree.

Dr. E.V. Anoop
Associate Professor and Head
Department of Wood Science
College of Forestry,
Kerala Agricultural University
Vellanikkara, Thrissur, Kerala
(Chairman)

Dr. A.V. Santhoshkumar
Associate Professor and Head
Department of Tree Physiology and Breeding
College of Forestry,
Kerala Agricultural University
Vellanikkara, Thrissur, Kerala
(Member)

Dr. T.K. Kunhamu
Associate Professor and Head
Department of Silviculture and Agroforestry
College of Forestry,
Kerala Agricultural University
Vellanikkara, Thrissur, Kerala
(Member)

Dr. S. Gopakumar
Associate Professor,
Department of Tree Physiology and Breeding
College of Forestry,
Kerala Agricultural University
Vellanikkara, Thrissur, Kerala
(Member)

EXTERNAL EXAMINER

ACKNOWLEDGEMENT

*With deep esteem I evince my heartfelt gratitude and owe to my major advisor **Dr. E.V. Anoop**, Associate Professor and Head, Department of Wood Science, College of Forestry for his valuable guidance, support, inspiration, critical advise, encouragement and friendly cooperation throughout the course of my research work. Words are not enough to express my gratitude and respect for him. I consider myself lucky to have him as my advisor.*

*I extend my wholehearted thanks to **Dr. A.V, Santhoshkumar** Associate Professor and Head, Department of Tree Physiology and Breeding, College of Forestry and member of advisory committee for his keen interest and valuable suggestions he has provided throughout the course of my study.*

*I owe my sincere thanks to my advisory committee member **Dr. T.K, Kunhamu**, Associate Professor and Head, Dept. of Silviculture and Agroforestry, College of Forestry, for his cooperation and intellectual advice extended to me during the course of my study.*

*My earnest thanks to **Dr. S. Gopakumar**, Associate Professor, Dept. of Forest Management and Utilization, College of Forestry and advisory committee member for the whole hearted cooperation and valuable advice to me during the study.*

*I take this opportunity to recognise **Dr. K, Vidyasagaranan**, Dean, College of Forestry for his support during the study.*

*I also recognise **Dr. K, Sudhakara** former Dean, College of Forestry for his support during the earlier stages of my study.*

*My earnest thanks are due to **Dr. S.S. Chauhan**, Scientist, Institute of Wood Science and Technology and **Dr. A. Nicodemus** Scientist-F, Institute of Forest Genetics and Tree Breeding, Coimbatore, for their whole hearted cooperation and intellectual advice to me during the course of study.*

*I am wholeheartedly obliged to **Dr. Jimmy Thomas**, Wood technologist, and **Mrs. C.E. Jayasree** Central Wood Testing Laboratory, Kottayam for their timely advice and constant aid in a way of extending the facilities available in the institute for conducting the present study.*

Many thanks are due to **Kerala Forest Department**, and **Mr. Rakesh K, Ramdas**, RFO, Olavakkode Range, Palakkad forest division, for help rendered to carrying out the research work and for providing field staff in the aid of the same.

The help rendered by **Ms. Jayasree, Mr. Prasanth, Ms. Sofia, Mr. Ranjith, Mr. Syam Babu, Mr. Vishnu H Das, Mr. Muhammed Faisal Mr. Ajay Shankar,** in helping me during field and office works is also remembered with immense gratitude.

Words cannot really express the true friendship that I relished with **Mr Paul C Roby, Mr. Sachin K Aravind, Mr. Kiran Thomas, Mr. Ashish Alex, Mr. Raneesh, Mr. Mobin, Mr. Fredy, Mr. Tej karan, Mr. Sumith, Ms. Lakshmi Mr. Anand, Mr. Bill Mr. Subu, Mr. Akhil, Mr. Alex, Mr. Toji, Mr. Sreejith, Mr. Azar and Mr. Abin** for the heartfelt help and back-up which gave me enough mental strength to get through all mind-numbing circumstances.

Special mention for **Mr. Sreejith Babu and Ms. Anju S. Viijayan** for showing me how to carry out the research work through their experiences in the field, **Mr. Anish, M.C.** and **Mr. Vishnu, R** for their immense co-operation and helping mentality in making me understand the aspects of my research work. Words are not enough to show my gratitude to my dear **Longi (Mr. Anoob Prakash)** for being that special friend, everyone would always need to be in company with, at the time you most need it.

I also take this opportunity to express my deep rooted gratitude and amity to my dear friend **Jilna Joy** whose friendship I will always cherish and was pivotal in helping me get through the difficult times in the research. The company of **Shamily, Remya, Jeeshma, Abhirami and Athira** in the dull days of research will always be remembered with fond memories.

At this juncture, I express my deep love to my caring and tolerant **mother** and my dear **brother** without whose moral support, blessing and affection this would not have reached its fruition. I express my unexplainable love to my **father** for his blessings which signature the quality of my life.

Above all I bow my head to **THE ALMIGHTY** whose blessings enabled me to undertake this venture successfully.

JILJITH K P

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

INTRODUCTION

All differences among trees are the result of three things; the differing environments in which the trees grow, the genetic difference among trees, and the interaction between the tree genotype and the environment in which they grow (Zobel and Talbert, 1984). In forest trees, variation exist in different categories which can be broadly grouped as variability within species, provenances, stands, sites and individual trees (Zobel et al., 1960). Even when growing in the same stand, individual trees of a species often vary a great deal from one another. This is the major type of genetic variation used in selection and breeding programs (Zobel and Talbert, 1984).

Genetic variability is complex, but if its magnitude and type are known, it can be manipulated to obtain good gain in some tree characteristics (Zobel and Talbert, 1984). Characters such as wood specific gravity, bole straightness, and other quality characters of trees have stronger additive variance components than growth characteristics (Zobel and Talbert, 1984). The response to selection of characteristics with considerable non additive variance, is generally less satisfactory than for the characteristics that are usually under additive genetic control (Stonecypher et al., 1973).

Teak (*Tectona grandis* L.f.) is recognized for its physical and aesthetic qualities as one of the most important and valuable hardwoods in the world (Keogh, 1979, 2009; Tewari, 1992). With the diminishing availability of teak from natural forests to meet such a huge global demand of teak products, plantations prove to be important in meeting the mounting demand for timber. Thus, for many tropical countries, teak represents the best opportunity to produce quality timber and is of major importance to their forestry economies (Keogh, 1996). At present, the area of the planted teak forests reported by 38 countries is estimated to be 4,346 million ha, of which 83% is in Asia, 11% in Africa, and 6% in tropical America (Kollert and Cherubini, 2012). So, it is imperative that planting stock of high genetic quality should be used to increase the yield from plantations.

Most of the teak growing countries are now taking up more and more tree improvement programs that aim at achieving superior rate of growth and timber quality by means of selection and breeding. Tree breeding programs for teak have been established in south-east Asian countries for developing more productive teak forests (Soerianegara and Lemmens, 1994). Genetic improvement programmes in teak were initiated in India by the Forest Research Institute (FRI), Dehra Dun in 1962. Based on the methodology developed, action programmes were started to select plus trees to establish seed stands and clonal seed orchards. As a result, plus tree selection, establishment of seed stands and clonal seed orchards progressed well in India. In southern India, provenance trials, Clonal Seed Orchards and Seedling Seed Orchards have been established by various research organizations such as the Institute of Forest Genetics and Tree Breeding (IFGTB), Coimbatore and the Kerala Forest Research Institute (KFRI), Peechi and by the forest departments, particularly in Kerala and Tamil Nadu.

Tree breeding programs for teak have primarily targeted breeding of trees with superior growth characteristics, such as diameter, height, stem form, and pest resistance (Soerianegara and Lemmens, 1994; Callister and Collins, 2008; Monteuuis et al., 2011). Such selection criteria might have an indirect effect on wood properties (Zobel and Jett, 1995). Therefore, it is essential to know the nature and magnitude of the relationship between growth traits, wood density and other quality traits. The relationship between growth rate and wood density has been studied intensively, but the results obtained are often contradictory. Zobel and van Buijtenen (1989) had emphasised that wood quality improvement should be included as an integral part of any tree breeding program. Thus, of late, there has been a focus on improving wood properties by tree breeding in several hardwood species including teak (Kjaer et al., 1995).

In particular, the fundamental wood properties determining structural timber quality are density, modulus of elasticity (stiffness) and modulus of rupture (Karlinasari et al., 2008). Wood density is one of the more heritable and economically important traits. Therefore, it is highly desirable to include this trait in the tree improvement programmes in combination with other traits like growth, quality, pest resistance etc. Many of the tree improvement programmes have wood density as one of the selection criteria (Zobel and Jett, 1995). Thus, measuring this intrinsic characters in the standing trees is crucial in tree improvement programmes.

However, the measurement of wood density and modulus of elasticity (MOE) is constrained by various factors. Measurement in standing trees is costly in terms of man power and money because it involves extraction and processing of increment cores, discs or sticks, which involve destructive sampling. Because of the time and costs involved, destructive analysis in the trial will have to be restricted to fewer samples. Also, the samples may not be a good representative if only few trees are included. In many species, especially in priced timbers, it is extremely difficult to gather specimens. Many a times, the logs used in such tests cannot be retrieved for further utilization, incurring huge losses.

On the contrary, Non-Destructive Techniques (NDT) and Semi Destructive Techniques (SDT) have evolved worldwide, which helps to save precious resources without sacrificing logs for testing and have been found to be reasonably good predictors of timber properties under field conditions. Non-destructive evaluation (NDE) is the science of identifying the physical and mechanical properties of a material without altering its end-use capabilities. These modern NDT technologies find a place in assessing the physical and mechanical properties of standing trees at various ages as well. It can be used to understand the variation in timber properties such as basic wood density and MOE between the different seed sources, stands, as well as between the trees. Understanding genetic variations in wood properties of standing trees and their relation with growth traits will help in developing appropriate selection strategies for the teak tree improvement programmes and can provide early gain in such programmes.

Therefore, the present study is aimed at analysing the variation in wood basic density and dynamic modulus of elasticity of standing trees of teak grown in tree improvement trials at various locations in Kerala using destructive and non-destructive testing methods. It is also intended to determine the genetic variation in the above properties as well as to determine their relationship with growth traits in these trials.

REVIEW OF LITERATURE

Because of its natural origin, wood persistently exhibits an unusually wide degree of variation in both physical and mechanical properties as a result of its genetic source, environmental factors and also its complex internal multicomponent structure. These variations effect the suitability of wood for a wide range of purposes. Consequently,users and manufacturers of wood products are often chaotic about these wide deviations in wood properties and are interested to know the assets and potential of wood or timber as a raw material in advance, for conversion to various products (Dundar et al., 2012).

The main features required for solid wood products are its stiffness, strength, dimensional stability and lack of internal checking, crook, bow etc. (Raymond and Apiolaza, 2004). Basically, the fundamental wood properties determining these product quality are basic density, modulus of elasticity and modulus of rupture (Karlinasari et al., 2008).

2.1 VARIABILITY STUDIES

Even in intensively managed forests consisting of evenly aged single species stands there will be considerable, between site and between tree variation in the physical and mechanical properties of the collected wood. (Searles and Moore, 2009).In a study by Wei and Borralho (1997)in 4 *Eucalyptus urophylla* progeny trials in south east China, wood basic density based on increment cores and Pilodyn penetration were assessed and the results showed that both basic density and Pilodyn pin penetration are under strong genetic control, with heritabilityof 0.71 and 0.64, respectively. In the same study they also concludes that wood basic density had weak unfavourable genetic correlations with diameter, height and volume growth.

Callister and Collins (2008) collected and analysed data from a 3.5-year-old teak progeny test of clonal replications located in the northern part of Australia and found that, those teak clones had a narrow-sense heritability of

(0.22) for diameter and(0.18) for height. In the same study they obtained broad-sense heritability value of (0.37) for diameter and (0.28) for height.

Lan (2011) found that in *E.urophylla* progeny trials, growth traits (h^2 = 0.05-0.39) were found to be in low to moderate additive genetic control, whereas wood properties (h^2 = 0.35-0.66) were found to be under moderate to strong additive genetic control. A study in *E.globulus* by Muneri and Raymond (2000) found very diverse patterns of genetic variation in diameter at breast height, wood basic density, and pulp yield, predicted using near infrared reflectance analysis. For diameter at breast height there was comparatively little difference amongst the provenances studied and a low narrow sense heritability value (h^2 of 0.16 to 0.33), while wood basic density showed to have very large provenance differences along with high heritability (h^2 of 0.67 to 1).

In case of mechanical properties, wood stiffness was observed to have h^2 value of (0.57) in an analysis of open pollinated 8-year old *E. grandis* trees by Santos et al. (2004). In another study by Sotelo Montes et al. (2006) in open pollinated *Calycophyllum spruceanum* species of age 3.3-years h^2 for stiffness was found to be (0.47). Similarly for strength properties Henson et al. (2004) got h^2value as (0.57) in the 9 years old *E. dunnii* trees.

Hidayati et al. (2013) analysed 21 provenances of 24 year old teak trees in Indonesia, to characterise variation in tree growth properties, Stress wave velocity (SWV), and Pilodyn pin penetration depth (PPD) among the provenances. Significant differences was observed for all measured characteristics among the provenances, signifying that these characteristics are genetically controlled. Broad-sense heritability of growth characteristics, SWV, and PPD were moderate. The results from this study indicate potential scope for improving growth characteristics and wood properties of teak trees with the help of breeding programs. They had observed highly significant positive correlations among the growth characteristics, suggesting that they are closely related. In contrast, no significant correlations were observed between growth characteristics and SWV, indicating that they are independent of each other and they concluded that mechanical properties are also important criteria for selecting plus trees in tree breeding programs.

Kien et al. (2007)estimated genetic influence of wood basic density and pilodyn pin penetration and their relationship with diameter at breast height, height, stem straightness and branch size in two thinned, open pollinated progeny trials of *E.urophylla* in northern Vietnam at the age of eight and nine years. Wood basic density, assessed from 5 mm increment cores taken at breast height, averaged 510 kgm^{-3}across the two trials. Estimated narrow sense individual tree heritability (h^2) for wood basic density was 0.60, and that for pilodyn pin penetration was 0.42.The estimated genetic correlation between pilodyn penetration and wood basic density was -0.86, indicating that pilodyn could be used reliably as an indirect measurement of wood basic density. The estimated genetic correlations among wood basic density and diameter at breast height, height, stem straightness and branch size at each site were weak. Estimated genetic correlations between sites for both wood basic density and pilodyn pin penetration were high, indicating low genotype-by-environment interaction for these traits.

Subramanian et al. (2012) states that the main objectives of teak improvement and breeding programmes is to attain, superior stem form and timber quality, fast growth (height and diameter), a trunk free from fluting, buttressing and epicormic branches, resistance to leaf skeletoniser, defoliator, drought and frost, by selection and breeding activities. The teak forests of India are classified into five major types, based on rainfall, mainly as very dry; dry; semi-moist; moist and very moist types. Distinct genetic variation can be found in teak in the above mentioned types, and this has to be taken into consideration when going for the tree improvement programmes of teak.

Raymond (2002) states that for forecasting values at harvest, the suitable age at which each and every wood property may be assessed reliably is imperative. The earlier the wood property is evaluated, the more swift selections are done for breeding, and the greater rate of genetic gain per unit time is achieved. Conclusions about when and how to estimate different wood properties must be constructed on the patterns of transformation over time and the accurateness of the assessment method. For many wood properties there isn’t much information available about patterns of change with respect to change in age, so it is not possible to suggest suitable ages for accurate assessment.

2.1.1 DENSITY

The terms density and specific gravity in wood are both used to describe the mass of a wood material per unit volume and is the sum total of the wood substance proper, extraneous matter and wood content (Sekhar, 1988). These terms are often used interchangeably although they each have precise and different definitions (Bowyer and Smith, 1998).

In a species, the wood density is the most important wood characteristic because knowledge about it allows the estimation of a greater number of properties than any other trait (Bowyer and Smith, 1998).Wood density is considered the best single index of wood quality because it is the most dependable characteristic for predicting timber strength (Shirin et al., 1998).It affects various products of wood, such as pulp and paper properties, wood strength, and wood quality (Zobel and van Buijtenen, 1989). It has been a desirable trait to include in tree improvement programs because of its economic value and high degree of genetic control (Sprague et al., 1983)

It can be used as a predictor of yield and quality of pulp and paper products (Dadswell and Wardrop, 1959; Barefoot et al., 1970).Density seems to influence machinability, conversion, strength, paper yield and many other properties (Wimmer at al., 2002). Most mechanical properties of wood are closely related to specific gravity and density (Walker, 1993; Haygreen and Bowyer, 1996).Jerome et al. (2006) reported that wood density is the single best descriptor of wood; it correlates with many morphological, mechanical, physiological and ecological properties.

Wood density can be changed by silvicultural manipulations (Williams and Hamilton, 1961). Specific gravity varies with species and provenance. Edaphic, climatic and topographic factors profoundly influence specific gravity of wood. Parolin and Ferriera (1998) studied thirty five central Amazonian tree species and concluded that the specific gravity of wood from soils with low nutrient status was generally higher than that of wood grown in soils with higher nutrient status. Tree age is another factor which influences specific gravity. They also found that along with increase in tree age, specific gravity also increased from 0.47 to 0.56 in the case of *Acacia mangium*.

Usually basic density is assessed using a core taken near breast height, which seems to be highly correlated with the whole tree values for the character (Lausberg et al., 1995; Raymond and Muneri, 2001; Kube and Raymond, 2002).At the anatomical level, many characteristics influence density including cell wall thickness, cell diameter, growth ring width, amount of ray and vessel elements, and the early-wood to late-wood ratio in a growth ring. It is a complex feature influenced by cell wall thickness, proportion of different tissues, and the percentage of lignin, cellulose and extractives (Valente et al., 1992).

Shanavas and Kumar (2006) found that the presence of lignin and other denser fractions and/or complex wood ultra-structure, apparently enhances wood density, which explains the observed interspecific variations. With regard to within tree variation, mean specific gravity of heartwood is greater than sapwood and bark, presumably because of higher lignification in the former. The specific gravity of heart wood, sap wood and bark of *Artocarpus heterophyllus* were 0.534, 0.588 and 0.415 respectively. The specific gravity of heart wood, sap wood and bark of *Artocarpus hirsutus*are 0.523, 0.482 and 0.400 respectively in this study. Wood density also increased from the inner to outer positions along the radial direction for the two acacias.

Wood density varies within the tree also. Raymond and Macdonald (1998) assessed the longitudinal patterns of variation within trees for basic density in *Eucalyptus globulus* (ages 5 and 10 years) and *E. nitens* (ages 5, 10 and 15 years) plantations growing in three geographic areas in Tasmania. Each tree was sampled by taking discs from different percentage heights (0, 10, and 20 etc.up to 70%) and fixed heights (0.5 m, 0.7 m to 1.5 m). Both species showed an initial drop in density between the felling cut (zero height) and 0.5 m, followed by a linear increase in density between 10% and 70% of tree height. Density at all fixed heights was highly correlated with the whole tree values in*E. globulus*, but results were variable across sites for *E. nitens*. For *E. globulus*, the optimal sampling height was 1.3 m above ground and for *E. nitens*, optimal sampling height was 1.5 m above ground.

There are several ways to determine density from increment core samples. Gravimetric methods for density determination make use of the accurate determination of the volume and mass of the sample at specific moisture content (Yao, 1968).

2.1.2 MECHANICAL PROPERTIES OF WOOD

The strength properties of wood is influenced by various factors. The variation in wood strength properties between different species or within the same species can be due to both environmental and genetic influences (Schniewind, 1989). Bhat et al. (1999) showed that age has not much affect over the mechanical properties in some species. Mechanical property varies with respect to position of sample as well. In most of the cases, strength initially increase and then decrease again in the radial direction from pith to periphery (Sekhar and Negi, 1966; Sekhar, 1988). Presence of knots is an important factor affecting the strength property of timber (Rajput et al., 1998).

Accurate prediction of mechanical properties of standing trees has various benefits for farmers who raise timber trees for structural purposes (Wessels et al., 2011).This helps in better assessment of the resource quality (Kabir et al., 2002; Cown, 2005; Chauhan and Walker, 2006), better board segregation into various stiffness classes, and early screening for the genetic heritability for the same character (Kumar et al., 2002) and for better log segregation based on quality classes (Dickson et al., 2004; Amishev, 2008), and also to support tree breeders in screening and selecting for superior planting material (Launay et al., 2002; Lindstrom et al., 2002; Ivkovic et al., 2009).

According to Sekhar and Gulati (1972) and Limaye (1954) one individual timber is not likely to be better or worse than the other under all the tests and all the properties evaluated from these tests, suitability indices are derived by combining several properties relevant to a particular use and expressing them as percentage of reference timber so as to obtain a single figure for comparison.

Moisture content also influence mechanical properties, dry samples are found to have higher strength than green samples. However, above fibre saturation point, the mechanical properties are not much affected by moisture content (Kumar et al., 1987).

2.1.2.1 Static bending test

Stiffness-strength relationships in *Albizzia procera* and *Prosopis juliflora* was investigated by Lohani and Sharma (2003) by subjecting the samples to static bending test. The values for modulus of elasticity and modulus of rupture obtained from these tests revealed its possibility in machine grading. Shukla et al. (1988) by studying the strength properties based on static bending test, compression parallel to grain test and hardness test concluded that overall strength properties increased from pith to periphery in the heartwood and decreased in the sapwood region in 16 year old *Eucalyptus tereticornis* trees.

Kubojima et al. (2000) analysed the results of static bending and impact bending of heat-treated wood. In the initial stage of the heat treatment bending strength was found to increase and in later stages it was found to decrease. The work needed for rupture decreased steadily as the heating time increased. In the study it was concluded that heat-treated wood was comparatively more brittle than the untreated wood. They also states that the main factors contributing to the reduction of work needed for rupture were viscosity and plasticity, and not elasticity.

Kretschmann and Green (1996) reported that the elastic modulus increased with decreasing moisture content from green to four per cent moisture content. For finding this they analyzed various mechanical properties of clear southern pine at different moisture contents.

Sadegh and Rakhshani (2011) analysed beach wood for the static bending strength and compared them with other beech species. For this, randomly selected logs obtained from trees naturally growing in Noshahr region of Iran was tested according to ASTM Standards. In the study the static bending strength of beech was obtained as 1292 kg cm-^{2} and this value was compared with other available values in the literature, which revealed that beech trees growing in Iran have similar values for mechanical properties and density when compared to those growing elsewhere.

Influence of loading point on the static bending test of *Liriodendron tulipifera* wood was studied by Yoshihara and Fakuda (1998). They observed that, loading point had little influence in Young's and shear moduli at high depth/span ratio. In this situation the bending strength also increased.

Lin et al. (1999) analysed the variation pattern of mechanical property of *Dendrocalamus latiflorus* timber and revealed that site condition had no effect on the bending strength (Lin et al., 1999). Shepard and Schottafer (1992) found that, age profoundly influences bending strength properties. In a study conducted on red pine (*Pinus resinosa*), they revealed that modulus of elasticity and modulus of rupture was 22 to 90 percent greater in mature wood than in juvenile wood.

Ayarkwa et al. (2001) evaluated modulus of rupture of solid and finger jointed tropical African hardwoods using longitudinal vibration. They concluded that although static bending is generally recognized as a more desirable method of determining modulus of rupture, the longitudinal vibration technique may also be useful as a non-destructive technique for predicting modulus of rupture of solid and finger jointed African hardwood timbers.

Dhanya (2012) compared results of static bending test in seven species namely *Acacia auriculiformis, Artocarpus hirsutus, Artocarpus heterophyllus, Swietenia macrophylla, Xylia dolabriformis, Hevea braziliensis and Tectona grandis* and found that properties like Modulus of rupture, Maximum load, Fibre stress at limit of proportionality (FS at LP), Horizontal shear stress at limit of proportionality (HS at LP), Horizontal shear stress at maximum load (HS at ML), and Modulus of elasticity deferred significantly between all the species studied. In the study, *Tectona grandis* showed significantly higher value in tests like Maximum load, HS at LP, FS at LP and static MOE.

2.1.2.2 Compression parallel to grain

Results of compression parallel to grain test are particularly useful for evaluating suitability of timber species for post, poles and other industrial works where pressure on the wood act in a direction parallel to the grain of timber (Sekhar, 1988).

Dhanya (2012) compared results of compression parallel to grain test in seven species including *Tectona grandis* and found that properties like CS at LP, CS at ML and static MOE differed significantly among the species. In the study *Tectona grandis* proved to have higher value of static MOE (59469.31 kg cm^{-2}) compared to all species studied except *Xylia dolabriformis*.

Shukla et al. (1988). Studied, variation in strength properties within individual trees from pith to periphery in *Eucalyptus terreticornis*. He observed that compression strength parallel to grain increased from pith to periphery in heartwood, and in sapwood it decreased. In another study Rajput et al. (1997) determined the variation in specific gravity and compression parallel to grain among different clones of *Populus deltoides*, it was reported that maximum crushing stress differed significantly among clones and within individuals with respect to the radial position

Analysis of compression strength parallel to grain in woods of poplar, fir and spruce at different moisture content was done by Kolin (1988) at of 4% to 24% moister content and at different temperature falling between 20^{o} to 80^{o} C. He found compression strength to be decreased with increasing moisture content and temperature.

Oh (1997) studied the relationship between anatomical properties and compression parallel to grain in *Pinus densiflora*. From the studies he reported that compression strength parallel to grain increased with increase in tracheid length and wall thickness.

Razali and Hamami (1993) reported a mean maximum crushing stress of 43.4 N/mm^2 for 12- year old *Acacia mangium*, whereas Damodaran and Chacko

(1999) reported a mean maximum crushing stress of 30.4 N/mm^2 for 8 –year old and 10-year old *Acacia mangium* trees and concluded that compression parallel to grain is also affected by rate of growth and age of trees.

2.1.2.3 Compression perpendicular to grain

The compression perpendicular to grain test evaluates properties useful in sorting timber species put into uses where lateral surface of the timber experience the applied load such as railway sleepers, furniture, instruments and some type of sports goods (Sekhar, 1988). Beaudoin et al. (1989) studied on the mechanical properties of natural and plantation grown tamarack and concluded that compression perpendicular to grain and hardness properties was similar for trees growing in both conditions. Dhanya (2012) compared results of compression perpendicular to grain test in seven species including *Tectona grandis* and found that CS at LP was significantly different among all the species studied.

Compressive stress at limit of proportionality, compressive stress at maximum load, and modulus of elasticity in compression along perpendicular direction of grain increased from inner to outer positions in *Acacia mangium*. (Shanavas and Kumar, 2006). In clear southern pine trees compression strength perpendicular to grain increased with decreasing moisture content from green to four percent moisture content (Kretschmann and Green, 1996).

2.1.2.4 Hardness

Shukla et al. (2007) studied the mechanical properties plantation grown trees of *Acacia auriculiformis* of ages 8, 12 and 13 years From Sirsi, Karnataka, India. In the study it was found that the hardness and tension values determined in radial, tangential and end directions and tension perpendicular to the grain appear to be independent of age. The shear values were found to be related with age. The results suggest that if trees are allowed to grow older to attain greater size the range of potential uses will increase.

Dhanya (2012) compared results of hardness test in seven species including *Tectona grandis* and found that hardness in wood along the radial, tangential and end directions was significantly different among all the species studied.

Shanavas and Kumar (2006) analysed the hardness properties in *Acacia auriculiformis, A. mangium* and *Grevillea robusta.* Hardness in radial and tangential planes of *A. auriculiformis* was higher than that of *A. mangium and G.robusta*. Specimens collected from the mid position of *A. auriculiformis* had significantly higher radial and tangential hardness than that of inner and outer positions, while the other species did not show any predictable pattern. End-hardness decreased progressively from inner to outer positions in *A. auriculiformis*.

2.1.2.5 Shear strength

Maximum shearing strength is useful in selecting various articles such as agricultural implements, lorry bodies, bearing, packing blocks and so on (Sekhar, 1988). Yoshihara and Satoh (2003) had put forward off axis tension test method to determine shear strength by analysing the strength properties of *Fraxinus spaethiana* but they concluded later in the study that the method is not suitable to determine shear properties of wood. Sretenovic et al. (2004) assessed Norway spruce and European larch for the suitability of modified shear test set up upon block shear test and concluded that modified shear test is very suitable for determination of shear strength and shear modulus. Muller et al. (2004) further used the same method to determine the longitudinal shear modulus and shear strength of solid wood in a single test and observed that the shear properties of normal wood and compression wood of *Larix decidua* were related to wood properties like density, microfibril angle and lignin content

Lin et al. (1999) had assessed the variation pattern of mechanical properties in *Dendrocalamus latiflorus*. They concluded that site quality had no significant impact on shearing strength parallel to grain but age has a positive influence on shearing strength. Rokeya et al. (2010) in their study reported that in air dry conditions the strength values of wood for compression perpendicular to grain, hardness and shear parallel to grain are higher than that of the green conditions except for nail withdrawal.

Dhanya (2012) compared results of shear strength test in seven species including *Tectona grandis* and found that the load sustained by *Tectona grandis* (2396.04 kg cm^{-2}) and *Swietenia macrophylla* (2225.10 kg cm^{-2}) was the lowest. The maximum shear stress was also low for *Tectona grandis* (95.84 kg cm^{-2})

2.1.2.6 Tensile strength parallel to grain

Rokeya et al. (2010) studied on the physical and mechanical properties of hybrid Acacia (*Acacia auriculiformis* x *Acacia mangium*) and reported that the values of tension perpendicular to grain are lower for samples at dry conditions than those in green conditions. Krestchmann and Green (1996) analysed the relationship between moisture content and mechanical properties in clear southern pine. They found that the tensile stress parallel and perpendicular to grain increased with decreasing moisture content. They observed it reached a peak value between 7% and 13% moisture content. Hildebrandt (1960) studied the importance of chemical composition in mechanical wood properties and its influence on the same. And reported that the tensile strength, resistance to rupture and shock increased as the amount of lignin decreased.

Dhanya (2012) compared results of tensile strength parallel to grain test, in seven species including *Tectona grandis* and found that *Tectona grandis* (685.25 kg cm^{-2}) had the highest tensile stress at limit of proportionality. The values of tensile stress at maximum load obtained for *Acacia auriculiformis* (1273.51 kg cm^{-2}) was found to be the highest followed by *Tectona grandis* (1193.98 kg cm^{-2}) and all the species studied differed significantly with respect to both the properties mentioned.

2.1.2.7 Dynamic MOE

Stiffness referred as the dynamic modulus of elasticity is the one of the foremost criteria for machine stress grading of sawn or converted timber, and has a key influence on the price. However, it is not a parameter that is usually measured in standing trees or logs. Derivation of an alternate easy indicator for wood stiffness would expedite and facilitate more efficient planning and effective log sorting, it would also provide a valuable tool for breeding and silviculture enthusiasts working on standing trees (Dickson et al., 2004).

In a study by Wang et al. (2001) a total of 159 red and jack pine logs were analysed from northern Michigan non-destructively and statistical comparison was done between stiffness and MOE. The results from these investigates show that red pine and jack pine logs of small-diameter can be effectively evaluated using techniques like longitudinal stress wave, transverse vibration, or static bending. The dynamic MOE (MOE stress wave and MOE vibration) of logs was observed to be well correlated with the static MOE in the case of both species.

Acoustic tools have been used to calculate dynamic modulus of elasticity, which is found to have usually higher value compared to static modulus of elasticity which is determined using destructive bending tests. Nevertheless, laboratory analysis shows that there exist a strong relationship (R^2>0.9) between dynamic MOE and its static counterpart for small and defect less samples and the sawn timber. This is the main reason for including acoustic machines in grading processes of sawn timber. Also, these results show that portable tools based on resonance can be put to use in the prediction of mechanical properties of a large-section of timber and poles which would otherwise only be visually inspected. (Mochan et al., 2009).

Dhanya et al. (2014) observed significant positive correlation between dynamic modulus of elasticity (MOE) and static MOE. Dynamic MOE was found to be significantly correlated with all the parameters obtained from static bending test like modulus of rupture (MOR), modulus of elasticity (MOE), fibre stress at elastic limit, horizontal shear stress at limit of proportionality and horizontal shear stress at maximum load in this study. It was also noticed that dynamic MOE showed significant correlation (5 % level) with radial and tangential hardness. Regression was also done between dynamic MOE and static MOE among the species. The R^2 value obtained was 0.77.

2.2 NON DESTRUCTIVE EVALUATION

Non-destructive evaluation (NDE) of a material is, by definition, the science of analysing the physical as well as mechanical properties of a piece of material without altering or changing its end-use capabilities.

2.2.1 PILODYN

Pilodyn penetration correlated well with crushing strength and MOE besides density in the case of hardwood species like maple and oak (Chudnoff et al., 1984). Wu et al. (2010) tested the effectiveness of Pilodynin evaluating wood basic density, outer wood density, heartwood density, and modulus of elasticity (MOE) in 22 four year old eucalyptus clones in Guangxi, China. Results indicated that the mean value of Pilodyn pin penetration, wood basic density and MOE ranged from 9.44 to 15.41 mm, 0.3514 to 0.4913 g cm-3 and 3.94 to 7.53 GPa, respectively. There were significant differences (1% level) in Pilodyn pin penetration depth between the different treatments, along different directions and between the various clones. Generally strong negative correlations were found between Pilodyn pin penetration depth and wood properties, and the coefficients value ranged from (-0.433) to (-0.755).The results confirmed that Pilodyn is an effective and efficient means of estimating wood properties.

Dhanya et al. (2012) found that Pearson’s bivariate correlation coefficient (R) between air dry specific gravity and penetration depth ranged from -0.94 (teak) to -0.56 (rubber wood). A similar pattern was observed in oven dry specific gravity and the correlation coefficient ranged from -0.91 (teak) to -0.71 (rubber wood). The higher values for correlation coefficient obtained in this study compared with others might be due to the fact that Pilodyn pin penetration was made directly into the end cross section of the logs along the grain and not through the bark or the outer wood. Hence, the results obtained in this study confirms that Pilodyn holds great potential in rapid screening of logs for wood specific gravity. They also observed significant negative correlation (1% level) between specific gravity (oven dry) and pilodyn pin penetration depth between the species. Highest correlation was observed in *Tectona grandis* and the lowest in *Hevea brasiliensis*. Negative correlation was also noticed between specific gravity at pith, middle and periphery regions and penetration depth at these positions. Specific gravity (air dry) was also found to be significantly correlated with pilodyn penetration depth in all the species except rubber wood (*Hevea brasiliensis*). Significant negative correlation was found for pin penetration depth with modulus of rupture, horizontal shear stress at maximum load and dynamic MOE. Significant correlation (5% level) was also found between penetration depth with radial hardness, horizontal shear stress at limit of proportionality and fibre stress at limit of proportionality. Regression analysis done between pilodyn pin penetration depth and specific gravity (oven dry), revealed that a linear relationship exists between them. R^2 value obtained for the species ranged from 0.51 to 0.82. The highest R^2 value was observed in *Tectona grandis* and the lowest was in *Hevea brasiliensis*. A linear relationship was also noticed between penetration depth and specific gravity (air dry).

2.2.2 TREE SONIC TIMER

Eckard (2007) assessed the efficiency of the tree sonic time-of-flight acoustic tool at screening young clones of loblolly pine for three economically important solid wood properties: wood density, modulus of rupture (MOR), and modulus of elasticity (MOE). Tree sonic stress wave speed measurements (SWS) were highly repeatable (r = 0.85) and had moderate and highly significant clone mean correlations with mechanical wood properties. SWS were largely uncorrelated with wood density. Thus, SWS was highly efficient at selecting clones for MOE (r = 0.81), moderate for MOR (r = 0.59) and poor for density (r = 0.03).

Stress wave based non-destructive evaluation methods were used in evaluating the quality and modulus of elasticity of wood in the used Douglas fir treated with preservatives and southern pine piles by Wang et al. (2000). Stress wave propagation speeds in the piles were obtained to estimate their MOE, followed by a few sequence of tests on boards, and on small, clear wood specimens obtained from the piles. Regression analyses conducted revealed that a strong correlation exist between the stress-wave-based MOE (dynamic MOE) of piles and the corresponding flexural properties of boards and small, clear wood specimens obtained by transverse vibration and static bending techniques.

Searles and Moore (2009) found that, portable stress-wave based tools deliver a cost effective means of forecasting the stiffness or elastic properties in standing tree or in logs. In the application of stress-wave-based tools to the Sitka spruce supply chain in the UK, there was a strong relationship exhibited between the mean modulus of elasticity of the timber cut from a particular site and the mean stress wave velocity measured for trees at the same site (R2=0.76).

Ross and Pellerin (1991), based on the results obtained from 113 green Douglas-fir mill run dimension lumber specimens (12 ft. x 2 in. x 4 in.) from a local lumber mill in Washington. They concluded that longitudinal stress wave nondestructive evaluation techniques may be useful in assessing the modulus of elasticity of green material.

Wang et al. (2000) found that the stress wave passed through the wood behaved differently in logs when compared to small, clear wood specimens and lumber and explained it to be because of the relative large size of the logs. As the wave travels in the longitudinal direction of a log, the outer portion of the wood may have a governing effect on the propagation of waves. This leads to higher stress wave velocity in a log compared with the small, clear specimens cut from the same log, which increased the value of MOE_{sw} and in turn overestimated the MOE of the log. It was also observed that the diameter-length ratio can also be a critical factor affecting the stress wave behavior in logs.

Wang et al. (2001) found that by using stress wave propagation based methods MOE can be computed using velocity v and the mass density of the material ρ using the equation $MOE = \rho \times v^2$.Although this equation was derived for an idealized, one dimensional case, it has been observed to exist also for actual three dimensional cases as well, as long as the length of the wave is large relative to the lateral dimensions of the material. Round and straight logs produced better correlation between dynamic MOE and static MOE than the logs that were of inconsistent dimensions. Similarly, the diameter-length ratio (D/L)also had a decisive effect contributing significantly when used in the analysis of dynamic

MOE. The multivariate model relating static MOE to dynamic MOE and diameter-length ratio was found a better predictor in static MOE predictions of logs. This could facilitate the prediction of properties related to static bending of logs using stress wave based techniques at levels of accuracy which was previously considered unattainable.

Gray et al. (2008) found significant relationship between average stress wave velocity and moisture content. Their study suggests that increase in moisture content reduced the stress wave velocity and this variation needs to be considered seriously when performing non-destructive evaluation using stress wave velocity. They studied 100 yellow-poplar (*Liriodendron tulipifera*) specimens by passing stress waves five times through each specimen over a distance of 0.635 meters and the average stress wave velocity obtained was used in the comparisons. Observations were taken on a daily basis for average dimensions, mass, and stress wave velocity as the specimens gradually air-dried. The study was concluded once the specimens dried down to approximately 10 percent moisture content.

Wang et al. (2001) revealed a strong relationship between SWS in trees and in small, clear specimens. The correlation coefficient (r = 0.83) found was highly significant at 0.01 confidence level. They suggests that the stress wave based non-destructive evaluation technique used in their study provided reliably accurate stress wave information, there by strengthening the argument for using such instruments in the prediction of wood properties in standing trees. Statistical analyses indicate that strong relationships exist between the stress wave properties in standing trees and the strength and stiffness properties associated with the small clear specimens taken from the same trees.

Mochan et al. (2009) compared the results of resonance measurements and the time-of-flight measurements taken on standing trees taken on logs cut from same trees. It showed that, there exist strong relationship between stress wave velocity measured using the two different methods. The correlation between the readings of the two instruments indicate that it is possible to make reliable estimates of wood stiffness in a plantation before a tree is felled.

The study by Chauhan and Walker (2006), shows that within the same stand acoustic velocity was found more variable than the peripheral wood basic density, it signifies the prominence of acoustic velocity as a better parameter in the screening based on the outer wood modulus of elasticity (MOE). Strong positive relationship was observed between the acoustic velocity measured on standing trees using the instruments, Fakopp and Hitman ST 300on butt logs of the corresponding logs obtained from same trees. The Fakopp instrument gave higher velocity on an average by 9% in the 8 and 16 year old trees and up to 17% higher in the 25-year-old trees. Though a justifiably good correlation was observed between the velocities obtained, the strength of comparison was poorer in the 25 year old stand. Some trees exhibited huge difference (25– 30%) in the two velocities obtained. They point out this difference to be due to the tree diameter, stand age and the bark proportion on the trees and also to be due to presence of a knot or any such defects in the area through which the wave propagate. Though the relationship between log basic density and acoustic velocity was very weak for young stands, it was found to be improved in the older stands.

2.3. GROWTH TRAITS

The segregation of trees and logs has often been made on the basis of external characteristics. While this generally provides valuable information on the volume of timber that can be recovered, it is not a good indicator of the mechanical properties of this timber (Wagner et al., 2003).Tree breeding programs for teak have primarily targeted breeding of trees with superior growth characteristics, such as diameter, height, stem form, and pest resistance (Soerianegara and Lemmens, 1994; Callister and Collins, 2008; Monteuuis et al. 2011). Such selection criteria might have an indirect effect on wood properties (Zobel and Jett, 1995). Therefore, it is essential to know the nature and magnitude of the relationship between growth traits, wood density and other quality traits.

Lan(2011) found that there was no significant relationship between growth traits and wood properties (Pilodyn penetration, basic density or acoustic velocity squared), but observed strong negative correlation between Pilodyn penetration and acoustic velocity squared (rg = -0.76 to -0.53). Also basic density and Pilodyn penetration were highly negatively correlated (rg = -0.95 to -1.00).

MATERIALS AND METHODS

3.1 MATERIALS

3.1.1 Species studied

The species studied was teak (*Tectona grandis* L.f.) and is locally known as thekku. Its wood is moderately hard and moderately heavy and is medium coarse textured with straight grain and is ring porous. Heartwood and sapwood are distinct from each other. Sapwood is white or pale yellow, heartwood is light golden brown when fresh, turning brown or golden brown on exposure, often with darker streaks. The wood has an attractive figure produced by distinct growth rings. The wood has the smell of old leather. The wood is well known for its good quality and is often used as a standard for comparison for other timbers. It has a wide range of uses; from ship building, construction, panelling, interior fittings, railway sleepers, furniture and cabinet making. It is an outstanding timber for joinery. Because of its resistance to chemicals it is used in industrial chemical plants.

3.1.2 Location

The study was done in three different teak growing districts of the state, namely Palakkad, Malappuram and Thrissur. The study areas included a Clonal Seed Orchard (CSO, Walayar, Palakkad), Seed Production Area (SPA, Nilambur, Malappuram) and clonal trial plots (Chettikkulam and Vellikulangara, Thrissur), the locations of which are shown in fig. 1 and field pictures in Plate 1.

3.1.2.1 ***Walayar***

The study area is located at Vattapara (10°49'38" N and 76°49'14" E), 3 km west, of the Walayar forest check post and is a Clonal Seed Orchard raised and maintained by the Institute of Forest Genetics and Tree breeding (IFGTB), Coimbatore, established in the year 1978. The field was initially planted with 722 ramets belonging to 20 clones under completely randomised design in an area of 2.7 hectares out of which many trees had fallen naturally, reducing the number of ramets per clone drastically to the present situation of 10 clones from Tamilnadu, 9 from Kerala and 1 from Andhra Pradesh, making a total of 20 clones. This area has an average summer temperature of 40° C and average winter temperature of 20° C and compared to other parts of Kerala, the rainfall is very low.

3.1.2.2 ***Nilambur***

The study area is located at Cherupuzha (11°17'46" N and 76°21'21" E) near the Nedumkayam forest station of Nilambur (South) Forest Division. It is a Seed Production Area established in 1971 by the IFGTB Coimbatore in an area of about 71.11 ha. It was recently thinned to remove inferior trees by the score thinning method. The climate is tropical in Nilambur and has significant rainfall in most months, with a short dry season. The average annual temperature in Nilambur is 27.7 °C and the annual precipitation is about 2666 mm.

3.1.2.3 ***Chettikkulam and Vellikulangara***

Chettikkulam and Vellikulangara are located in Thrissur district and share almost similar edaphic and climatic features. The study area at Chettikkulam (10°20'34" N and 76°23'42" E) is an experimental plot of the Kerala Forest Research Institute (KFRI) which was established in the year 2001. The field trial is located near the Forest Range Office at Chettikkulam, Thrissur. The field is laid out with 16 clones of teak of various provenances of Kerala with a spacing of 2 m x 2 m. The trial at Vellikulangara (10°21'54" N and 76°24'27" E) was established in 2011 and is a clonal trial plot of the KFRI. These sites are characterised by warm, humid tropical climate with a mean maximum temperature ranging from 29.1˚C (July) to 36˚C (May) and the mean minimum temperature varying from 21.9˚C (January) to 25˚C (May) and an average mean annual rainfall of 2670 mm. The trial was established to evaluate the performance of the clones based on growth data.

3.1.2.4 ***Elival***

Elival is situated in the Olavakkode range of Palakkad division. The felling operations was conducted in the 1953 teak plantation near the Elival forest section office (10°55'40" N and 76°38'58" E). It is also a highly dry place similar to Walayar.

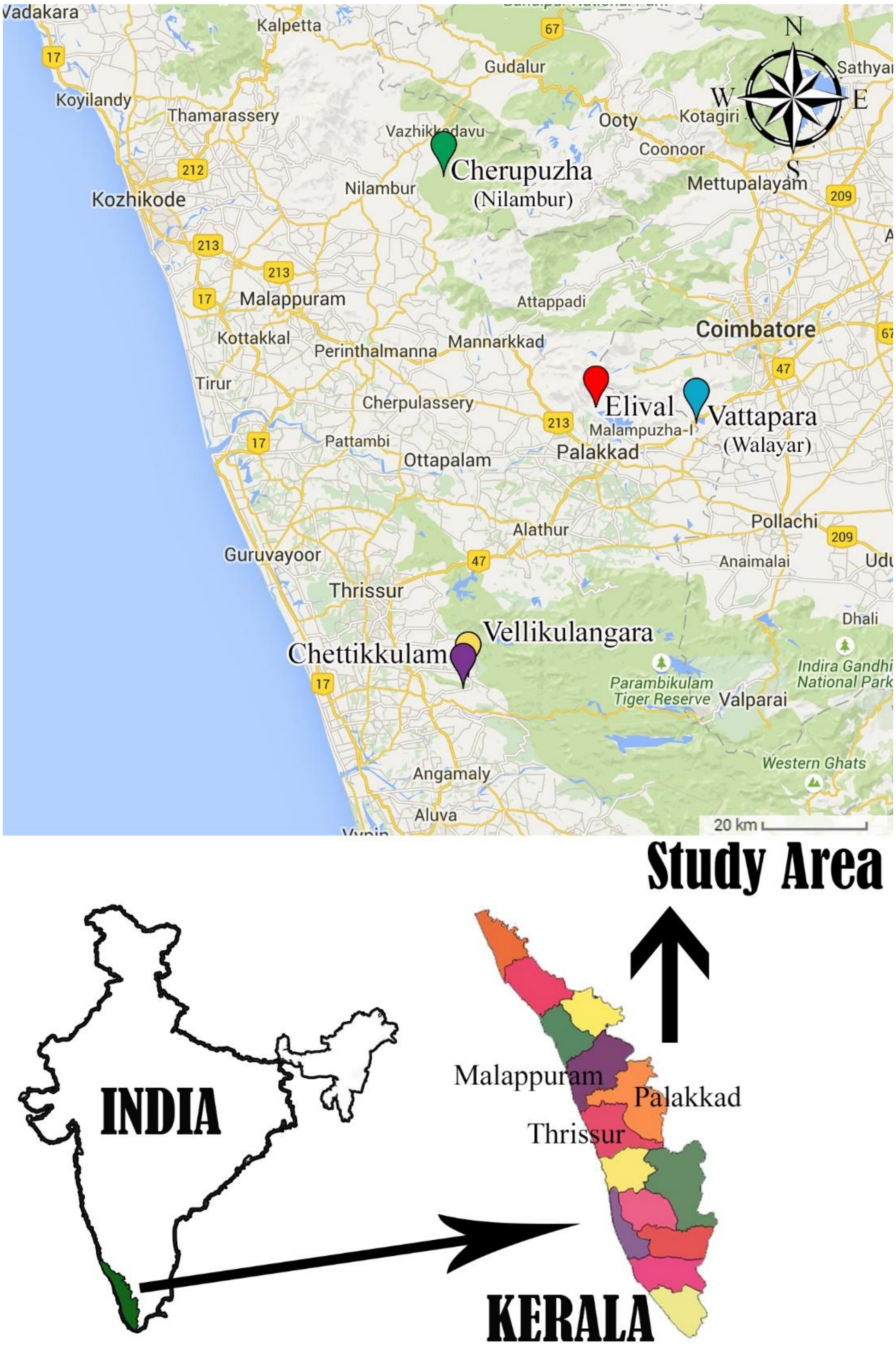


Figure 1. Map showing the location of the study sites.

3.2 METHODS

The following growth and non-destructive measurements were carried out on selected teak trees grown in the above mentioned trials at Walayar, Nilambur, Chettikkulam and Vellikulangara, the details of which is given in Table 1.

Table 1. Details of the trials in the study areas.

Sl. No.	Location	Trial type	Year of planting	Age	No. of trees studied	Treatment	Replication
1	Cherupuzha (Nilambur)	SPA	1971	43	100	Girth classes	5
2	Vattapara (Walayar)	CSO	1978	35	100	20 clones	5
3	Chettikkulam	Clonal trial	2001	13	60	10 clones	6
4	Vellikulangara	Clonal trial	2011	3	24	4 clones	6

Note: at chettikkulam increment cores were collected from 12 clones with 3 replication each and density analysis was done using these samples.

3.2.1 Measurement of growth characteristics

Growth characteristics such as total tree height, girth at the breast height, bole height and number of branches of the trees were measured. Height measurements were taken using a Haga altimeter. The Haga altimeter is a gravity-controlled pivoted pointer with a series of scales (15, 20, 25 and 30 m) and a percent scale. In the present study, the height measurements were obtained using the 15 m scale of the instrument. Girth was measured at breast height using a measuring tape (Plate 2 a). The number of branches were also counted.

3.2.2 Measurements using non-destructive instruments

Pilodyn and tree sonic micro second timer were the two non-destructive equipment used in this study.

3.2.2.1 ***Pilodyn measurement***

Pilodyn is an instrument used for indirect non-destructive assessment of basic density (Greaves et al., 1996 and Raymond and Macdonald, 1998) of logs as well as standing trees. The pilodyn drives a steel pin and the penetration (referred as pin penetration depth – PPD) is indicated on the instrument and is inversely proportional to the density of the wood (Hansen, 2000). In the present study, Pilodyn 6 J (FUJI TECK, Tokyo, Japan) with 2.5 mm pin diameter was used for taking measurements. Using pilodyn, readings were taken from all the trees under study in the field. First the bark was removed and its thickness was measured. In the present study PPD was taken from three sides of well grown standing trees at the breast height and their average was calculated for getting the PPD value representing a tree. In trees with lesser girth in Vellikulangara only one PPD reading was taken. The penetration depth was recorded by pressing the Pilodyn 6 J against the bark removed portion of the tree (Plate 2 c). Standing trees from all the trials studied was subjected to pilodyn measurements. PPD was assessed in the pith, middle and periphery regions of the collected discs also (Plate 5 b & c). The penetration was read in millimetres (0-40 mm) on the scale on one side of the instrument

3.2.2.2 ***Tree sonic micro second timer measurement***

Tree sonic micro second timer (Fakkopp, Hungary) is used to rapidly predict wood stiffness (MOE) of standing trees (Wang et al., 2000; Lindstorm et al., 2002; Kumar, 2004; Toulmin and Raymond, 2007; Dhanya et al., 2012). The instrument is designed and patented by Wayerhaeuser Co. (Chih-Lin, 2005). The timer consist of two transducers, the longer and flat shaped transducer with red mark is the start and the shorter and cube shaped one is the stop transducer. The transducers were inserted into the standing tree in such a way that they are 1 m apart from each other such that the tree breast height point comes between the two transducers. The start transducer was hit with a sliding hammer. The measurements were repeated thrice in each tree at two exactly opposite sides of the standing trees for well grown trees and three readings from just one side for small trees in Vellikulangara. The time required for the sound waves to pass from the start transducer to stop transducer through the log was noted from the timer. Three readings each were taken from both sides of the trees. Velocity was calculated by dividing the distance travelled by the stress wave by the time taken (Mochan, 2009). Dynamic MOE (Modulus of Elasticity) or stiffness was measured using the one dimensional relationship: $E = \rho \times v^2$, where E is the modulus of elasticity, ρ is the actual density of the wood at the time of measurement in Kg/m^3 and v is the velocity in m/s (Dhanya et. al., 2014, Chauhan et al., 2005; Chauhan and Walker, 2006; Lasserre et al., 2007) (Plate 2 d & e).

3.2.3 Measurements using destructive methods

Four trees were cut for destructive sampling from the 1953 teak plantation at Elival in Olavakkode Range of Palakkad Division (Plate 3 a & b) after taking the required readings using non-destructive instruments on these trees as per the methods mentioned in the previous section. 1.5 m long logs from the four trees of different girth classes were taken and scantlings were made from all the four geographic directions with respect to the standing position of each tree in the field as per the illustrated procedure for preparation of small clear specimens as per IS 2455: 1990 specified by ISI (1990).

3.2.3.1 *Analysis of within tree variation in pin penetration depth*

Pin penetration depth at the periphery, middle and pith of the discs from a position 50 cm from the base of the tree and logs, obtained from 1953 plantation near Elival forest station of Olavakkode range in Palakkad division was taken in all four directions with respect to the standing position of the tree, using Pilodyn (Plate 5 b & c).

3.2.3.2 ***Estimation of physical properties***

3.2.3.2.1 *Sample collection*

Density was estimated on core samples collected from a height of 1.37 m from ground of selected trees of each clones from Chettikkulam using presslers increment borer. Three trees were selected from each clone. Some clones only had two ramets in the plot, in such cases cores were collected from only two trees (Plate 2 b). Clones with three replications was used for genetic analysis and the rest were used for the correlation study alone. Clones used for analysing the genetic variation in the trait were T26, T21, T6, T5, T11, T27, T10, T46, T13, T47, T1 and UK1.

3.2.3.2.2 *Basic density*

Basic density (standard specific gravity) of each clone was determined using the formula,

$$\text{Basic wood density} = \frac{\text{Oven dry Weight}}{\text{Green Volume}}$$

Green volume was estimated by using the immersion method. In order to calculate oven dry weight, the samples were dried in an oven, set at an approximately constant temperature of $102^{\circ}C \pm 1^{\circ}C$, for such a time as is needed to make its weight constant. Then the weight of the oven dry samples were taken by using an electronic balance. The wood basic density was then computed using the above mentioned formula.

3.2.4 Estimation of mechanical properties

3.2.4.1 *Conversion of logs*

After taking the readings using pilodyn and treesonic microsecond timer, each of the logs was sawn to scantlings of size 6.5 cm x 6.5 cm cross section and 1.3 m length (Plate 4). These scantlings were taken to the Rubber Wood Testing Laboratory of Rubber Research Institute, Kottayam for further conversion to small clear specimens as per IS 2455: 1990 (ISI, 1990) for analysing the mechanical properties.

The tests for assessing mechanical properties of *Tectona grandis* were carried out as per IS 1708: 1986 (ISI, 1986) at the Rubber Wood Testing Laboratory of the Rubber Research Institute of India (RRII), Kottayam. Static bending strength, compression strength parallel to grain, compression strength perpendicular to grain, shear, tension parallel to grain and hardness were tested using an automatic ‘Universal Testing Machine’ (UTM-Shimadzu 100 Kg).

3.2.4.2 *Testing instrument*

All the mechanical properties were tested using an automatic Universal Testing Machine (UTM-Shimadzu 100 KgN) which is a computerized and sophisticated version of the manual UTM. The instrument (Plate 6) used in this study; the automatic Universal Testing machine (UTM, Shimadzu) is an assemblage of different units. The testing units consists of a jig where the samples are loaded for test and a head, whose upward or downward movement applies stress to the sample. The calibration of the instrument is controlled by a control keypad. This set up is associated with a computer installed with the software ‘Winsoft”, which sense the deflection and stress, and plots the load by deflection curve on the monitor simultaneously along with the test. Before the start of a test, the instrument is calibrated for the type of test, rate of loading, dimensions of sample as per IS 1708: 1986 (ISI, 1986). On completion of the test, the stress by strain graph can be directly read from the monitor and various parameters corresponding to the test can be recorded.

3.2.4.3 *Preparations of test samples*

Scantlings were allowed to air dry for few days. Then the scantlings were converted to standard small clear specimens for different tests as per IS 2455: 1990 specified by ISI (1990). The samples were air dried to a moisture content of 12 to 20 percent. The samples were transferred to a conditioning chamber (Plate 7) to condition all the samples to a uniform moisture percent of 12±2 per cent

3.2.4.4 *Testing of samples*

3.2.4.4.1 *Static bending test*

Samples of size 2 cm x 2 cm cross section and 30 cm length were tested as per IS 1708 (part 5): 1986 (ISI, 1986). Before loading the sample for testing, the width and thickness were accurately measured. The samples were loaded such that the stress was on the tangential plane (Plate 8). The machine was calibrated to set the deflection and load at zero and the rate of loading was set at 1mm/minute. Load by deflection curve was read from the monitor. The parameters viz., modulus of elasticity (MOE), modulus of rupture (MOR), maximum load, fibre stress at limit of proportionality (FS at LP) and horizontal shear at limit of proportionality (HS at ML) were recorded for further reanalysis.

Reanalysis of the derived data was done to calculate MOE accurately. The software calculates MOE over a range of deflection at limit of proportionality. To overcome this discrepancy, the tangent of the curve was adjusted to the maximum and deflection corresponding to the proportionality limit was recorded. By substituting the value thus attained in the following formulae, various parameters were reanalysed.

(a)	Fiber stress at limit of proportionality (Kg/cm^2) (FS at LP)	=	$3\,PI/2bh^2$
(b)	Modulus of rupture (Kg/cm^2) (MOR)	=	$3P'I/2bh^2$
(c)	Modulus of elasticity (Kg/cm^2) (MOE)	=	$PI^3/4\Delta BH^3$
(d)	Horizontal shear stress on neutral plane at limit of proportionality (Kg/cm^2) (HS at LP)	=	3P/4bh
(e)	Horizontal shear stress at maximum load (Kg/cm^2) (HS at ML)	=	3P'/4bh
(f)	Maximum Load (Kg) (ML)	=	CA"/ lbh

Where,

P	=	Load in Kg at the limit of proportionality which shall be taken as the point in load deflection curve above which the graph deviates from the straight line
I	=	Span of the test specimen in cm
b	=	Breadth of test specimen in cm
P'	=	Maximum load in Kg
Δ	=	Deflection in cm at the limit of proportionality
C	=	Area constant in Kg.cm (the energy represented by one square centimetre which is equal to load in Kg, represented by one square centimetre ordinate multiplied by deflection in centimetres,

represented by one centimetre abscissa).

A = Area in cm^2 of load deflection curve up to limit of proportionality

3.2.4.4.2 *Test for compression strength parallel to grain*

Samples of size 2 cm x 2 cm cross section and 8 cm length were tested as per IS 1708 (part 8): 1986 (ISI, 1986). Before test, the width, thickness and length of the samples were recorded. The rate of loading was calibrated to 0.6 mm/min and the load and deflection was set to zero. The sample was loaded with its longitudinal axis along the direction of movement of head (Plate 9). After the test, data is saved in a folder systematically. Load- deflection curve is analysed through the reanalysis mode. A tangent is drawn in such a way that maximum number of points are in the straight line. Based on the limit of proportionality and maximum load, the Compressive Stress at Limit Proportionality, Compressive Stress at Maximum Load and Modulus of Elasticity was calculated by using the formula given below.

(a)	Compressive stress at limit of proportionality (Kg/cm^2) (CS at LP)	=	P/A
(b)	Compressive stress at maximum load (Kg/cm^2) (CS at ML)	=	P'/A
(c)	Modulus of elasticity in compression parallel to grain (Kg/cm^2)	=	$LP/\Delta A$

Where,

P = Load at limit of proportionately in Kg

A = Cross sectional area of specimen in cm^2

P' = Maximum crushing load in Kg

L = Length of the specimen in cm

Δ = Deformation at the limit of proportionately in cm

3.2.4.4.3 *Test for compression strength perpendicular to grain*

Samples of size 2 cm x 2 cm cross section and 10 cm length were tested as per IS 1708 (Part 9): 1986 (ISI, 1986). The sample was loaded such that the tangential plane faces the stress (Plate 10). The linear dimensions of the sample were recorded before the test. Rate of loading was calibrated to 0.6 mm/minute and the deflection and load were set to zero. Various parameters were read from the monitor and graph adjusted to reanalyse the MOE. The following parameters were calculated using the formulae.

(a) Compressive stress at limit of proportionality (Kg/cm^2) = P/A

(b) Crushing strength at compression of 2.5 mm (Kg/cm^2) = P'/A

(c) Modulus of elasticity in compression parallel to grain (Kg/cm^2) = P/A x H/Δ

Where,

P = Load at limit of proportionately in Kg

A = Area of cross section normal to the direction of load or area of metal plate used is 3x2 cm.

P' = Load at 2.5 mm compression in Kg

H = Height of the specimen in cm

Δ = Deformation at the limit of proportionately in cm

3.2.4.4.4 *Hardness test*

Samples of size 5 cm and 5 cm cross section and 15 cm length were tested as per IS 1708 (part 10): 1986 (ISI, 1986) (Plate 11). Load (KN) required to penetrate into the specimen by a steel bar with a hemispherical end or a steel ball of 1.128 cm diameter to a depth of 0.564 cm was recorded. Measurements were made at the center of the radial, tangential and end faces and no splitting or chipping occurred. The rate of loading was kept constant at 6mm/minute.

3.2.4.4.5 *Shear test*

Samples of size 5 cm and 5 cm cross section and 6.25 cm length were tested as per IS 1708 (Part 11): 1986 (ISI, 1986). The specimens were notched at one end to produce shear failure in an area of 5 cm × 5 cm in the radial or tangential plane. The samples were loaded such that the head of the machine rests exactly in the notch (Plate 12). Rate of loading was calibrated to 0.4 mm/minute and the load and deflection were set to zero. Various parameters were analysed by the following formulae. Reanalysis was not done, as the parameters studied were independent of deflection at limit of proportionality.

Maximum shearing stress (Kg cm^{-2}) (M.S.S) = P/A

Where

P = Maximum load in Kg

A = Cross section area of specimen in cm^3

3.2.4.4.6 *Tensile strength parallel to grain*

Samples of 5 cm and 1.5 cm cross section and 32.5 cm in length were tested as per IS 1708 (part 12): 1986 (ISI, 1986) (Plate 13). The machine was calibrated to set the deflection and load at zero and the rate of loading was set at 1 mm/minute. Based on the limit of proportionality and maximum load, TS at LP and TS at ML were calculated by using the formula mentioned below.

Tensile stress at limit of proportionality (Kg/cm^2) (TS at LP) = P/A

Tensile stress at maximum load (Kg/cm^2) (TS at ML = P'/A

Where

P = Load at limit of proportionately in Kg

P' = Maximum load in Kg

A = Cross sectional area of specimen in cm^2

3.2.5 Statistical analysis

Data obtained were subjected to statistical analysis using SPSS (ver. 20). The tests used for the study included ANOVA with post hoc testing using Duncan's Multiple Range Tests (DMRT) and t-test. Correlation and regression analysis were done to find out the relation between measurements obtained destructively and non-destructively as well as between wood properties and growth characteristics. Variation between clones was assessed using one way ANOVA and genetic variation in the characters were analysed from this.

3.2.5.1 *Computation of genetic characteristics*

Computation of Diversity Parameters. Genotypic, phenotypic, and environmental variances were calculated using the following equations:

3.2.5.1.1 *Variances*

Genotypic variance$(Vg) = \frac{(Mt-Me)}{r}$, (1)

Where Mt = mean sum of square of treatment, Me = mean sum of square of error, and r = block replicates,

Environmental variance (Ve) = Me,

Phenotypic variance (Vp) = (Vg) + (Ve). (2)

Broad Sense Heritability (H^2). Heritability is the ratio of genetic variance to the total phenotypic variance and was calculated using equation

$$H^2 = \frac{V\,g}{Vp} \times 100, \quad (3)$$

Where H^2 =heritability in broad sense.

3.2.5.1.2 *Genetic Variability* / *Genetic advance*

Genetic advance (GA) is the expected increase in the magnitude of a particular character when a selection pressure of chosen intensity (i) is applied. This was calculated as per Johnson et al. using the equation.

Genetic Advance $GA = \frac{V\,g}{V\,p} \times K \times \sqrt{Vp}$ (4)

Where K =selection intensity.

3.2.5.1.3 *Genetic gain*.

Genetic gain expected in percent of mean was calculated using the formula given below Genetic gain = $\frac{GA}{X} \times 100$ (5)

Where X = total mean of the clones.

3.2.5.2 ***Clustering and clone selection***

Cluster analysis was done by wards method of hierarchical clustering analysis (Ashok and Gurumurthi, 1997) using SPSS v20. Dendrograms were prepared and the similar and dissimilar clusters of clones were analysed separately for the different study areas. The same clusters were used for selecting the superior clones with respect various important traits. The cluster having better mean value for the important traits and individuals with high value for the respective traits were selected.

a) 

b) 

b) 

d) 

Plate 1. View of study areas at a) Walayar (CSO) b) Nilambur (SPA) c) Chettikkulam (clonal trial plots) and d) Vellikulangara (clonal trial plots).

a) 

b) 

c) 

d) 

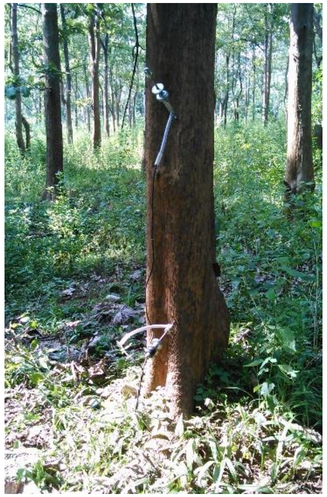
e) 

Plate 2. Pictures showing various field activities on standing trees, a) taking girth measurement of standing tree b) collecting core sample c) taking pilodyn penetration depth d) making treesonic timer reading and e) showing tree sonic timer set up on standing trees.

a

b

Plate 3. Felling operations (a and b) at Elival, Palakkad for collection of samples.

a

b

Plate 4. Sawing of logs using band saw (a) and further conversion using re-saw machine (b) to scantlings for conducting strength tests.

a)

b)

c)

Plate 5. a) Collection of discs from logs for conducting NDT measurements b) Discs showing positions at which measurements were taken at the end cross section of logs and discs using Pilodyn. c) Making Pilodyn penetration depth readings on the discs.

Plate 6. Universal Testing Machine (UTM)

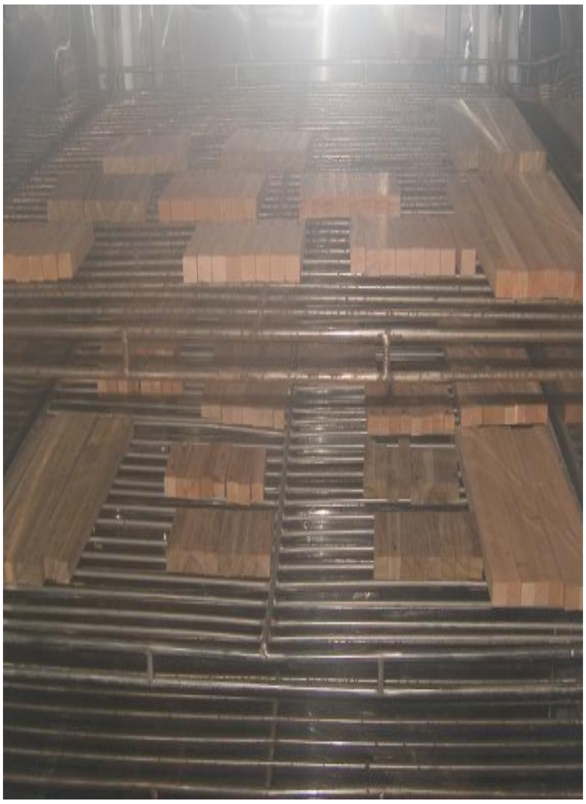


Plate 7. Wood samples kept for conditioning

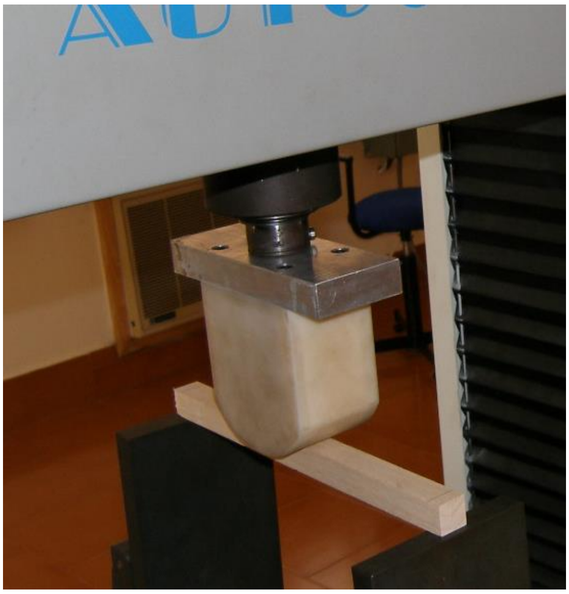


Plate 8. Static bending test

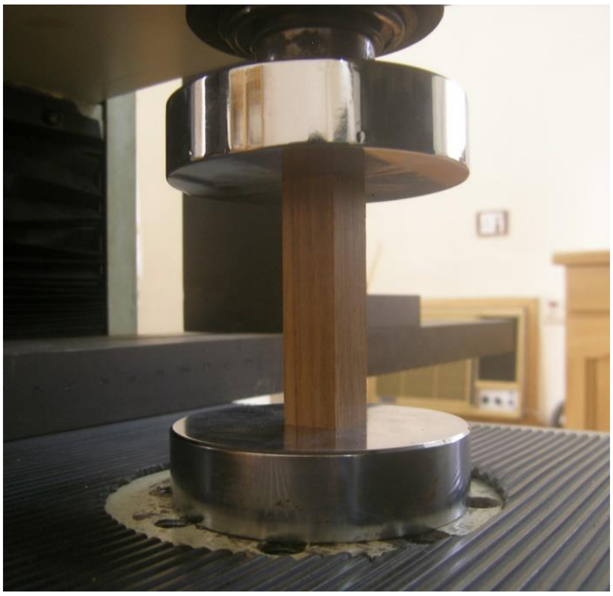


Plate 9. Test for compression strength parallel to grain

Plate 10. Test for compression strength perpendicular to grain

Plate 11. Test for hardness

Plate 12. Test for shear strength

Plate 13. Test for tensile strength parallel to grain

RESULTS

This chapter describes the results of various tests conducted destructively and nondestructively to analyze the wood physical, mechanical and growth properties in Teak grown at five different areas in the state of Kerala.

4.1 PHYSICAL PROPERTIES

4.1.1 Basic density (Destructively analysed using increment cores)

Basic density was found to be significantly different between the 12 clones studied at the 13 year old clonal trail at Chettikkulam. The mean specific gravity was found to be highest for the unknown clone marked as UK1 (589.83 kg/m3) and the lowest mean basic density was found for clone T5 (522.33) (Fig. 2).

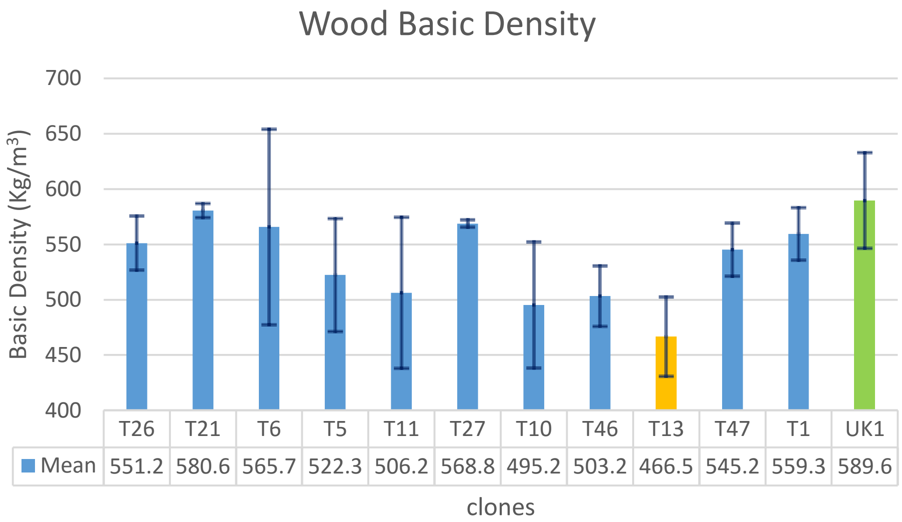


Fig. 2 Wood basic density variation in twelve 13-year old clones at Chettikkulam, Mean density and standard deviation are shown.

4.2 MECHANICAL PROPERTIES

4.2.1 Static bending test

4.2.1.1 Modulus of rupture

The data on variation in modulus of rupture between the four trees studied are presented in Table 2. Analysis of variance conducted revealed that all the trees differed significantly with respect to modulus of rupture. Table 2 reveals that tree numbered 1 had the highest MOR value (1225.29 kg cm^{-2}) and the tree numbered 4 (865.18 kg cm^{-2}) had the lowest value.

4.2.1.2 Maximum load

Maximum load sustained by tree number 1 (231.99 kg) was the highest of the four followed by tree number 2, both this trees was found to be significantly different from the other trees. It was also noticed that the load sustained by tree number 4 (164.86) was the lowest and was significantly different from all others (Table 2).

4.2.1.3 Fibre stress at limit of proportionality

From Table 2 it can be seen that in this property also the same trend was followed by the trees. Tree number 1 (833.12 kg m^{-2}) and tree number 2 (817.14 kg m^{-2}) was found to be homogenous and had higher values for the trait. Tree number 4 (554.50 kg m^{-2}) had the lowest value and was significantly different from all others.

4.2.1.4 Horizontal shear stress at limit of proportionality

Table 2 shows the variation in horizontal shear stress at limit of proportionality among the trees. All the trees differed significantly with tree number 1 (29.69 kg cm^{-2}) having the highest value followed by tree number 2 (29.05 kg cm^{-2}). It was also observed that the value obtained for tree number 4 (19.75 kg cm^{-2}) was the lowest.

4.2.1.5 Horizontal shear stress at maximum load

The data on variation in horizontal shear stress at maximum load among the species are presented in Table 2. Analysis of variance conducted revealed that all the trees differed significantly with respect to the values. Tree number 1(43.67 kg cm^{-2}), followed by tree number 2 (41.26 kg cm^{-2}) had higher values compared to other two trees. Here also tree number 4 (31.01) had the lowest value.

4.2.1.6 Modulus of elasticity

All the trees differed significantly with respect to static MOE value also, with tree number 1 (121712 kg cm^{-2}) having the highest value followed by tree number 2 (104539.42 kg cm^{-2}) and then by tree number 3 (103832.51 kg cm^{-2}). Here tree number 2 and 3 was found to be homogenous and (68827.71 kg cm^{-2}) tree number 4 (77715.26) had the least static MOE value (Table 2).

Table 2. Results of static bending test performed for the four teak trees obtained from Elival forest section, Olavakkode range

Tree no.	GBH	MOR (kg cm-^{2})	Max load (kg cm-^{2})	FS at LP (kg cm-^{2})	HS at LP (kg cm-^{2})	HS at ML (kg cm-^{2})	MOE (kg cm-^{2})
1	152	1225.29^{a} (55.14)	231.99^{a} (10.53)	833.12^{a} (68.69)	29.69^{a} (2.42)	43.67^{a} (1.96)	121712.77^{a} (9848.80)
2	106	1154.92^{a} (130.98)	218.69^{a} (24.68)	817.14^{a} (118.72)	29.05^{a} (4.16)	41.26^{a} (4.69)	104539.42^{b} (12840.91)
3	126	1040.44^{b} (112.44)	197.45^{b} (21.43)	659.65^{b} (80.86)	23.53^{b} (2.88)	37.10^{b} (4.03)	103832.51^{b} (12168.08)
4	92	865.18^{c} (142.24)	164.86^{c} (27.07)	554.50^{c} (81.81)	19.75^{c} (2.85)	31.01^{c} (5.17)	77715.26^{c} (10816.84)

Means with same letters as superscript within a column are at par, MOR – Modulus of rupture, Max load - Maximum load, FS at LP – Fibre stress at limit of proportionality, HS at LP – Horizontal shear stress at limit of proportionality, HS at ML – Horizontal shear stress at maximum load, MOE – Modulus of elasticity

4.2.2 Test for compression strength parallel to grain

4.2.2.1 Maximum load

Maximum load sustained by tree number 1 (2111.25 kg cm^{-2}) was significantly higher than all other trees (Table 3). The values obtained for tree number 2 (1908.06 kg cm^{-2}) and tree number 3 (1912 kg cm^{-2}) were homogeneous, and tree number 4 (1501.32 kg cm^{-2}) had the lowest value.

4.2.2.2 Compressive stress at limit of proportionality

Table 3 shows the variation in compressive stress at limit of proportionality among the trees studied. It was observed that all the trees differed significantly at 1 per cent level. Tree number 1 had the highest value (422.37 kg cm^{-2}) and tree number 4 had the lowest value (315.72 kg cm^{-2}).

4.2.2.3 Compressive stress at maximum load or Maximum crushing strength

The data on variation in Compressive stress at maximum load among the trees are presented in Table 3. Analysis of variance conducted revealed that all the species differed significantly at 1 per cent level with respect to this property. For this property also trees showed the same trend in the values as that obtained for maximum load.

4.2.2.4 Modulus of elasticity

Modulus of elasticity of tree number 3 was the highest (32981 kg cm^{-2}) (Table 3). The values obtained for tree number 1 (32712.69 kg cm^{-2}) was the second highest and it was followed by tree number 4 (29464.51 kg cm^{-2}). The lowest value for modulus of elasticity was obtained for tree number 2 (28594.01 kg cm^{-2}). But for this property no significant difference was obtained among the trees.

Table 3. Variation in compression strength parallel to grain of the teak tree logs obtained from Elival forest section, Olavakkode range.

SI. No	GBH	Max Load (kg)	CS at LP (kg cm-^{2})	CS at ML (kg cm-^{2})	MOE (kg cm-^{2})
1	152	2111.25^a (264.50)	422.37^a (75.84)	530.27^a (66.08)	32712.69 (10941.13)
2	106	1908.06^b (186.15)	378.17^b (32.13)	479.06^b (46.78)	28594.01 (5511.16)
3	126	1912.86^b (144.00)	373.83^b (40.51)	474.84^b (39.12)	32981.98 (8423.38)
4	92	1602.13^c (107.96)	315.72^c (27.63)	401.58^c (27.01)	29464.51 (4649.95)

Means with same letters as superscript within a column are at par, CS at LP – Compressive stress at limit of proportionality, CS at ML - Compressive stress at maximum load, MOE – Modulus of elasticity.

4.2.3 Compression strength perpendicular to grain

4.2.3.1 Compressive stress at limit of proportionality

Table 4 shows the variation in compressive stress at limit of proportionality among the trees. It was observed that all the trees differed significantly at 1 per cent level for the property. The values obtained for tree number 2 (15954.21 kg cm^{-2}) was found to be the highest. The other three trees was found to be homogenous with respect to the trait.

4.2.3.2 Compressive stress at 2.5 mm limit

The values obtained for tree number 2 was found to be the highest and differed significantly from the other trees (Table 4) and the remaining three trees was found to be homogenous.

4.2.3.3 Modulus of elasticity

For modulus of elasticity also the same trend was followed as shown in the other two tests of Compression strength perpendicular to grain. Tree number 2 had the highest value and differed significantly from the other three which were found to be homogenous to each other (Table 4).

Table 4. Variation in compression strength perpendicular to grain of the teak tree logs obtained from Elival forest section, Olavakkode range.

SI. No	GBH	CS at LP (kg cm-^{2})	CS at 2.5mm (kg cm-^{2})	MOE (kg cm^{-2})
1	152	79.08^b (7.99)	165.71^b (5.68)	11803.34^b (1201.57)
2	106	122.21^a (25.62)	214.97^a (27.13)	15954.21^a (1456.57)
3	126	86.32^b (16.05)	166.38^b (28.20)	11327.57^b (2001.40)
4	92	84.40^b (16.42)	156.37^b (18.91)	10630.39^b (1451.44)

Means with same letters as superscript within a column are at par, CS at LP – Compressive stress at limit of proportionality, CS at 2.5mm

4.2.4 Test for hardness

4.2.4.1 Radial

The data on variation in radial hardness among the trees are presented in Table 4. The value of radial hardness of tree number 2 (710.21 kg) was the highest and was significantly different from all other trees. Tree number 1 (622.61 kg) obtained second highest value and was also significantly different from all other trees. Tree number 3 and tree number 4 was homogenous and had lower value for the trait (Table 5).

4.2.4.2 Tangential

The values obtained for tangential hardness of tree number 2 (772.65 kg) was the highest followed by tree number 1 (627.94 kg). Tree number 4 (518.40 kg) had the lowest value. Tree number 3 (565.04) was homogenous to tree number

1 and tree number 4, but both this trees were significantly different from each other (Table 5).

4.2.4.3 Side

Side hardness also followed the same trend in values as in radial hardness. The similarity is clearly evident in the Table 4. Tree number 2 (741.43 kg) had the highest value and tree number 4 (505.78) had the lowest.

4.2.4.4 End

Tree number 2 (694.38 kg) had the highest value and tree number 3 (186.90 kg cm^{-2}) had the lowest value for end hardness (Table 4).

Table 5. Results of hardness test of the teak tree logs obtained from Elival forest section, Olavakkode range

SI. No	GBH	Radial (kg)	Tangential (kg)	Side (kg)	End (kg)
1	152	622.61^{b} (37.65)	627.94^{b} (39.54)	625.28^{b} (34.65)	573.99^{b} (35.33)
2	106	710.21^{a} (85.57)	772.65^{a} (55.63)	741.43^{a} (66.23)	694.38^{a} (71.05)
3	126	536.48^{c} (98.55)	565.04^{bc} (140.49)	550.76^{c} (109.18)	511.91^{c} (62.42)
4	92	493.16^{c} (27.72)	518.40^{c} (30.82)	505.78^{c} (26.78)	513.26^{c} (62.04)

Means with same letters as superscript within a column are at par

4.2.5 Test for tensile strength parallel to grain

4.2.5.1 Maximum load

Maximum load sustained by all the trees except tree number 4 was homogenous. The maximum load sustained by tree number 1 (631.99 kg) was the highest followed by tree number 3 (623.49 kg) and then tree number 2 (618.53

kg), which was found to have similar values (Table 6). Only tree number 4 (492.22) was found to be significantly different from all others, and it had the smallest value.

4.2.5.2 Tensile stress at limit of proportionality

At elastic limit, the values obtained for tree number 2 (632.39 kg cm^{-2}) was the highest, followed by tree number 1 (617.78 kg cm^{-2}) and tree number 3 (594.21 kg cm^{-2}) respectively, and tree number 4 (503.29 kg cm^{-2}) had the lowest tensile stress at limit of proportionality (Table 6). But these values were not significantly different from each other.

4.2.5.3 Tensile stress at maximum load

Tree number 4 (893.07 kg cm^{-2}) was the only tree found significantly different for this property and was found to be the lowest. Other three trees was homogenous with respect to the trait though tree number 2 had the highest value (1196.82 kg cm^{-2}) (Table 6).

4.2.5.3 Modulus of Elasticity

Modulus of elasticity with respect to tensile stress was also found to be significantly different among the trees studied. Tree number 2 (2520.37 kg cm^{-2}) had the highest value followed by tree number 1 (2301.48). Tree number 4 (1931.23 kg cm^{-2}) had the lowest value for the trait (Table 6).

Table 6. Variation in tensile strength parallel to grain of the teak tree logs obtained from Elival forest section, Olavakkode range.

SI. No	Species	Max Load (kg)	TS at LP (kg cm-^{2})	TS at ML (kg cm-^{2})	MOE (kg cm^{-2})
1	152	631.99^a (85.30)	617.78 (103.95)	1183.42^a (166.07)	2301.48^{ab} (253.11)
2	106	618.53^a (141.11)	632.39 (130.95)	1196.82^a (252.39)	2520.37^a (258.46)
3	126	623.49^a (141.08)	594.21 (171.78)	1171.25^a (255.87)	2172.03^{bc} (296.36)

4	92	492.22[b] (155.86)	503.29 (182.06)	893.07[b] (309.14)	1931.23[c] (414.87)

Means with same letters as superscript within a column are at par, Max load - Maximum load, TS at LP – Tensile stress at limit of proportionality, TS at ML – Tensile stress at maximum load

4.2.6 Shear strength

4.2.6.1 Maximum load

Maximum load with respect to both Radial and Tangential shear was found to follow same trend in the trees studied. All the trees was found to be significantly different for the trait which is evident in the Table 7.

4.2.6.2 Maximum shearing stress

Maximum shearing stress with respect to both Radial and Tangential shear was also found to follow the same trend as shown for maximum load in the trees studied. The trees was also found to be significantly different with respect to the trait (Table 7).

Table 7. Variation in shear strength of the teak tree logs obtained from Elival forest section, Olavakkode range

SI. No.	GBH	Radial Max Load	Radial MSS	Tangential Max Load	Tangential MSS	Average Max Load	Average MSS
1	152	3324.23[a] (179.26)	132.97[a] (7.17)	3633.87[a] (203.06)	145.35[a] (8.12)	3479.05[a] (152.75)	139.16[a] (6.11)
2	106	3354.90[a] (146.65)	134.20[a] (5.86)	3776.70[a] (266.80)	151.07[a] (10.67)	3565.80[a] (158.85)	142.63[a] (6.35)
3	126	3126.33[b] (244.33)	125.05[b] (9.77)	3236.43[b] (331.84)	129.46[b] (13.27)	3181.38[b] (245.62)	127.26[b] (9.82)
4	92	2874.47[c] (243.11)	114.98[c] (9.72)	3081.38[b] (207.20)	123.26[b] (8.29)	2977.92[c] (197.26)	119.12[c] (7.89)

Means with same letters as superscript within a column are at par, MSS – Maximum shear stress, Max load – Maximum load

4.3 NON DESTRUCTIVE EVALUATION

4.3.1 Pilodyn Penetration Depth (PPD).

Pilodyn penetration depth was found to be significantly different between clones of 35 year old CSO at Walayar (Table 8) and 13 year old trail at Chettikkulam (Table 9) but was not significantly different in the 3 year old clonal trail at Vellikulangara (Table 10). At Walayar, clone number KLN2 (15.11 mm) had the highest mean PPD value and clone TNT16 (11.19 mm) had the lowest (Fig. 3). At Chettikkulam, highest mean PPD value was found for clone T5 (14.87 mm) and lowest was for the unknown clone marked as UK (12.33) (Fig. 3).

Table 8. Pin Penetration Depth (PPD) variation among the 35 year old clones at Walayar, Palakkad

Clone	Mean	Minimum	Maximum	Std. Dev
KLS1	13.42^{cd}	13.17	13.70	0.24
KLS2	14.10^{abc}	13.93	14.30	0.15
KLS3	13.20^{cd}	11.67	14.87	1.18
KLS4	14.13^{abc}	13.75	14.60	0.36
KLN1	11.24^{f}	10.75	12.37	0.64
KLN2	15.11^{a}	14.20	16.40	1.05
KLN4	12.79^{de}	10.20	14.33	1.65
KLK1	14.96^{ab}	13.90	15.83	0.85
KLK2	13.41^{cd}	13.10	13.70	0.29
TNT1	14.03^{bc}	13.80	14.25	0.16
TNT3	11.94^{ef}	11.80	12.25	0.18
TNT4	13.46^{cd}	13.05	13.90	0.32
TNT5	13.12^{cd}	11.90	14.10	1.06
TNT6	13.89^{bcd}	12.75	15.10	0.91
TNT10	11.85^{ef}	10.80	13.75	1.15
TNT11	12.81^{de}	11.95	13.75	0.76
TNT15	12.81^{de}	12.25	13.30	0.48
TNT16	11.19^{f}	10.70	12.00	0.50
TNT20	11.84^{ef}	11.05	12.65	0.58

SBL1	13.76[cd]	13.10	14.20	0.41

Means with same letters as superscript within a column are at par

Table 9. Pin Penetration Depth (PPD) variation among the 13 year old clones at Chettikkulam, Trissure

Clone	Mean	Std. Deviation	Minimum	Maximum
T26	12.40[c]	0.64	11.40	13.00
T21	13.25[bc]	0.64	12.20	14.20
T6	14.23[ab]	0.79	13.00	15.20
T5	14.87[a]	1.40	13.00	17.00
T11	13.52[bc]	1.85	12.00	15.80
T27	12.93[c]	0.58	12.20	13.80
T10	14.32[ab]	0.93	13.20	16.00
T46	14.30[ab]	1.27	12.20	16.00
T47	12.40[c]	0.46	12.00	13.00
UK	12.33[c]	0.37	12.00	13.00

Means with same letters as superscript within a column are at par

Table 10. Pin Penetration Depth (PPD) variation among 3 year old clones at Vellikulangara, Trissure

Clone	Mean	Std. Deviation	Minimum	Maximum
1.00	10.53	0.74	10.00	12.00
2.00	11.12	0.24	10.80	11.50
3.00	10.53	0.83	10.00	12.20
4.00	11.40	0.69	10.20	12.00

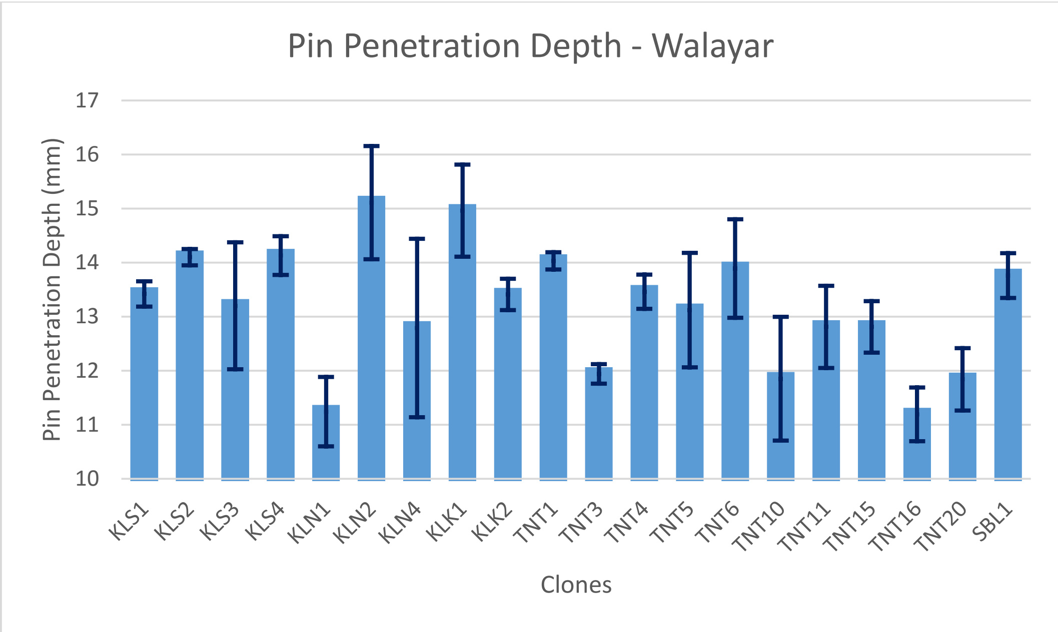


Fig. 3 Mean and standard deviation for Pin Penetration Depth of twenty 35-year old clones at Walayar

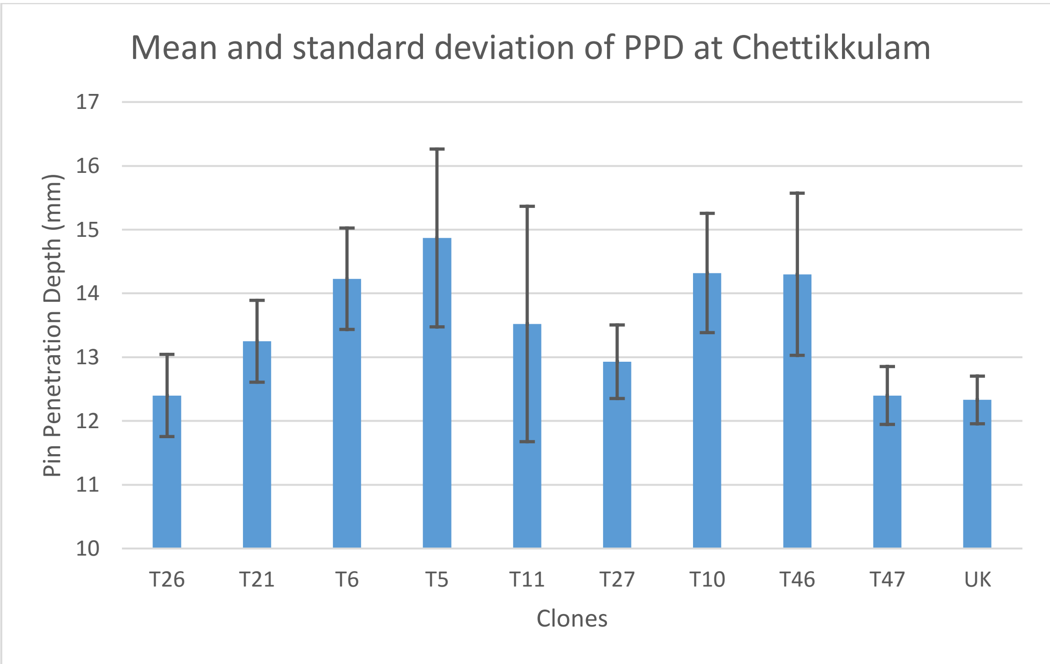


Fig. 4 Mean and standard deviation of PPD for ten 13-year old clones at Chettikkulam

4.3.2 Stress Wave Velocity (SWV)

Stress wave velocity was found to be significantly different among clones of Walayar and Chettikkulam (Table 11 & 12) but not between 3 years old clones at Vellikulangara (Table 13). At Walayar, clone TNT16 (3847 m/s) had the highest SWV value and clone TNT1 (3157 m/s) had the lowest (Fig. 5). At Chettikkulam, clone T47 (3598 m/s) had the highest SWV value and clone T6 (3212 m/s) had the lowest (Fig. 6).

Table 11. Comparison of Stress Wave Velocity (ms^{-1}) between the 35 year old clones at Walayar, Palakkad

Clone	Mean	Std. Deviation	Minimum	Maximum
KLS1	3376.49^{fghi}	81.09	3311.26	3502.63
KLS2	3519.51^{cdef}	61.40	3430.53	3597.12
KLS3	3485.45^{defg}	143.45	3305.79	3649.64
KLS4	3326.16^{ghi}	84.626	3231.02	3448.28
KLN1	3769.36^{ab}	163.01	3571.43	3929.27
KLN2	3357.74^{fghi}	133.50	3179.65	3496.50
KLN4	3675.94^{bc}	126.73	3490.40	3846.15
KLK1	3310.32^{hi}	136.93	3120.12	3502.63
KLK2	3412.17^{efgh}	108.91	3338.90	3597.12
TNT1	3157.56^{j}	169.62	3025.72	3436.43
TNT3	3481.54^{defg}	61.27	3412.97	3565.06
TNT4	3230.60^{ij}	50.32	3174.60	3278.69
TNT5	3521.84^{cdef}	159.63	3350.08	3766.48
TNT6	3329.13^{ghi}	74.44	3225.81	3401.36
TNT10	3569.88^{cde}	168.53	3424.66	3853.56
TNT11	3571.89^{cde}	45.69	3533.57	3649.64
TNT15	3654.33^{bc}	95.05	3496.50	3745.32
TNT16	3847.71^{a}	120.74	3724.39	4000.00
TNT20	3584.73^{cd}	89.57	3466.20	3717.47
SBL1	3594.92^{cd}	87.12	3514.94	3724.39

Means with same letters as superscript within a column are at par

Table 12. Comparison of stress wave velocity (ms^{-1}) between the 13 year old clones at Chettikkulam, Trissure

Clone	Mean	Std. Deviation	Minimum	Maximum
T26	3465.94^{abcd}	182.87	3278.69	3787.88
T21	3534.64^{abc}	146.58	3278.69	3703.70
T6	3211.95^{e}	80.63	3105.59	3333.33
T5	3377.12^{bcde}	51.17	3333.33	3460.21
T11	3348.01^{cde}	256.99	3048.78	3623.19
T27	3520.58^{abc}	122.13	3333.33	3636.36
T10	3532.41^{abc}	169.09	3215.43	3676.47
T46	3577.96^{ab}	169.97	3389.83	3861.00
T47	3597.67^{a}	176.48	3378.38	3906.25
UK	3281.06^{de}	96.76	3144.65	3424.66

Means with same letters as superscript within a column are at par

Table 13. Comparison of stress wave velocity (ms^{-1}) between the 3 year old clones at Vellikulangara, Trissure

Clone	Mean	Std. Deviation	Minimum	Maximum
1	3165.92	71.19	3048.78	3215.43
2	3240.13	122.96	3067.49	3412.97
3	3265.51	106.97	3174.60	3424.66
4	3360.21	233.12	3003.00	3649.64

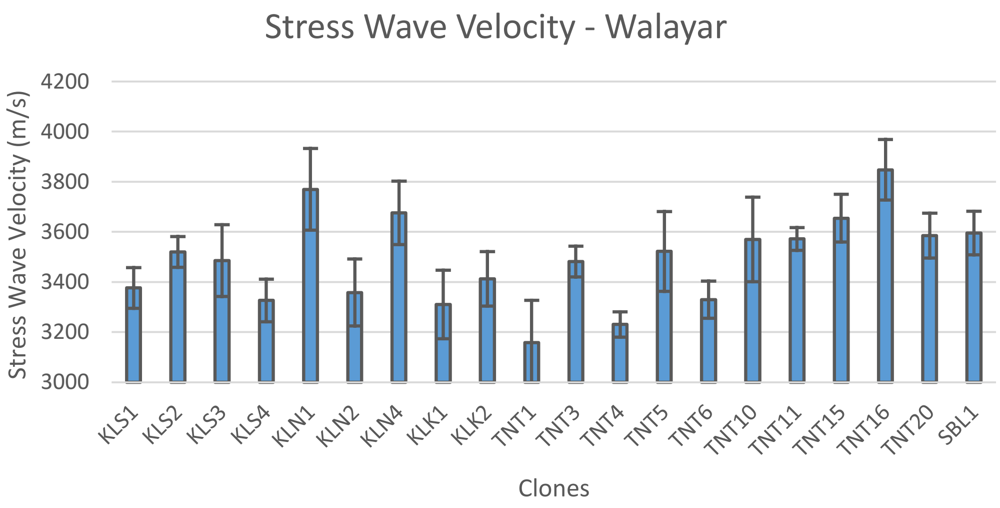


Fig. 5 Mean and standard deviation for Stress Wave Velocity (ms^{-1}) in twenty 35-year old clones at Walayar

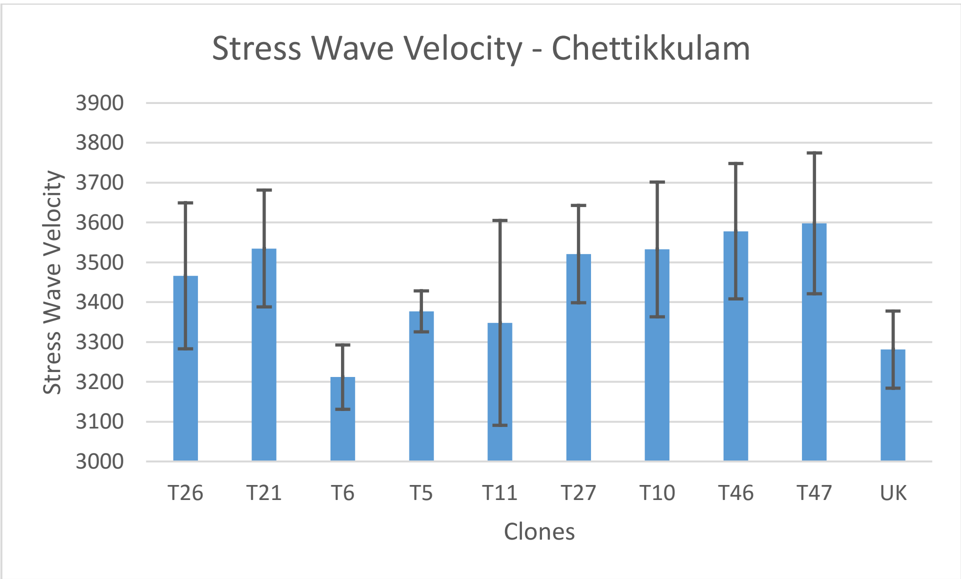


Fig. 6 Comparison of mean stress wave velocity (ms^{-1}) and its standard deviation for ten 13-year old clones at Chettikkulam

4.4 RELATIONSHIP BETWEEN DESTRUCTIVE AND NON DESTRUCTIVE METHODS IN WOOD PROPERTY DETERMINATION

4.4.1 Pilodyn Penetration Depth (PPD) vs Basic Density.

Pilodyn penetration depth was found to be negatively correlated with Basic Density in 44 trees studied at clonal trail plot at Chettikkulam with a correlation coefficient of (-0.642.) (Fig. 7). Mean PPD value of clones was also found to be negatively correlated with the mean specific gravity values of the same clones with a correlation coefficient of (-0.755).

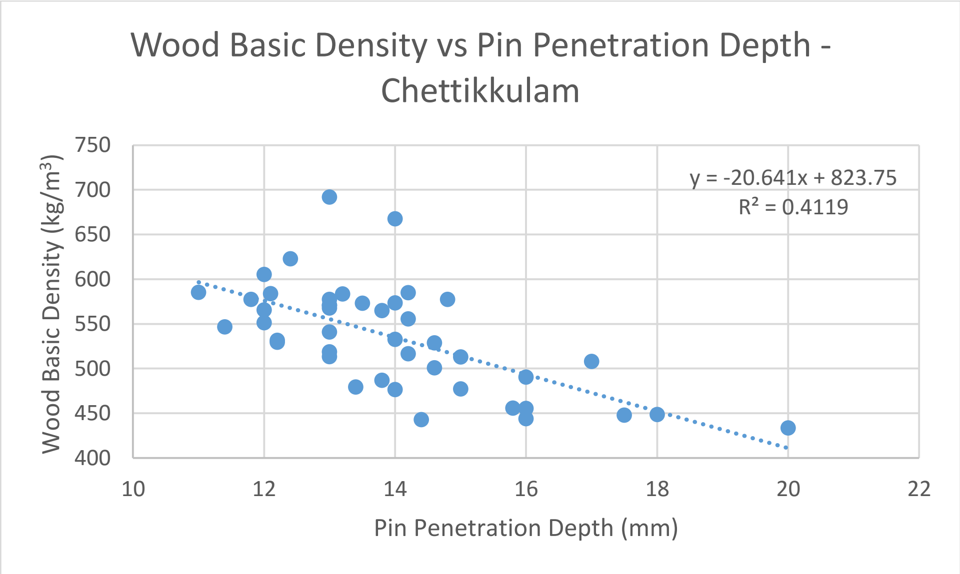


Fig. 7 Relationship between Density and Pin Penetration Depth for forty four 13 year old trees at Chettikkulam

4.4.2 Correlations within tree for PPD

PPD was found to have significant correlation at Periphery and Middle positions of the heartwood (0.416) but PPD at Pith was not having any significant correlation with PPD at Periphery or Middle position (Table 14). PPD at periphery was found to be lesser than PPD at other two positions almost consistently (Fig. 8).

Table 14. Correlation between PPD at pith, middle and periphery positions of tree discs and logs obtained from Elival forest section, Olavakkode range

	Periphery	Middle	Pith
Periphery	1	0.416*	-0.121
Middle	0.416*	1	0.281
Pith	-0.121	0.281	1

*. Correlation is significant at the 0.05 level.

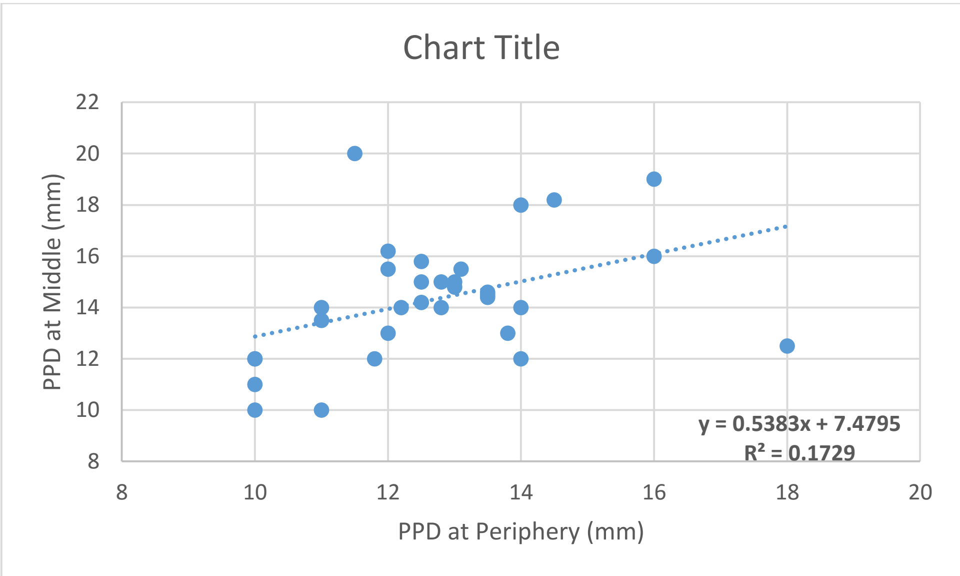


Fig. 8 Relationship between Pin Penetration Depth at middle and periphery positions in a tree.

4.4.3 Correlations with Mechanical Properties

Static MoE was found to have significant correlation with Stress Wave Velocity (0.991) and Dynamic MoE (0.989) derived from the velocity (Fig. 9 & 10).

Velocity also showed significant correlation with Modulus of rupture with a high correlation coefficient value (0.974). Similar was the case with maximum load (0.975) of static bending test, horizontal shear stress at maximum load (0.972) etc. many other mechanical properties estimated by destructive analysis using universal testing machine was also found to have high correlation with the Stress Wave Velocity estimated using the tree sonic timer (Table 15). With dMOE derived from the SWV also such high correlations was observed for many of the mechanical properties estimated destructively like MOR (0.971).

Table 15. Correlations between various mechanical properties and stress wave velocity in the four teak logs obtained from Elival forest section, Olavakkode range

Static bending test		Compression strength parallel to grain test		Tensile strength parallel to grain test	
MOR	0.974*	ML	0.988*	ML	0.879
ML	0.975*	CSatLP	0.996**	TSatLP	0.864
HSatML	0.972*	CSatML	0.995**	TSatML	0.850
HSatLP	0.919	Hardness test		MOE	0.710
FSatLP	0.916	RAD	0.657	Shear strength	
MOE	0.991**	TAN	0.523	MAX SS	0.836
		SIDE	0.588	MEAN SS	0.836

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

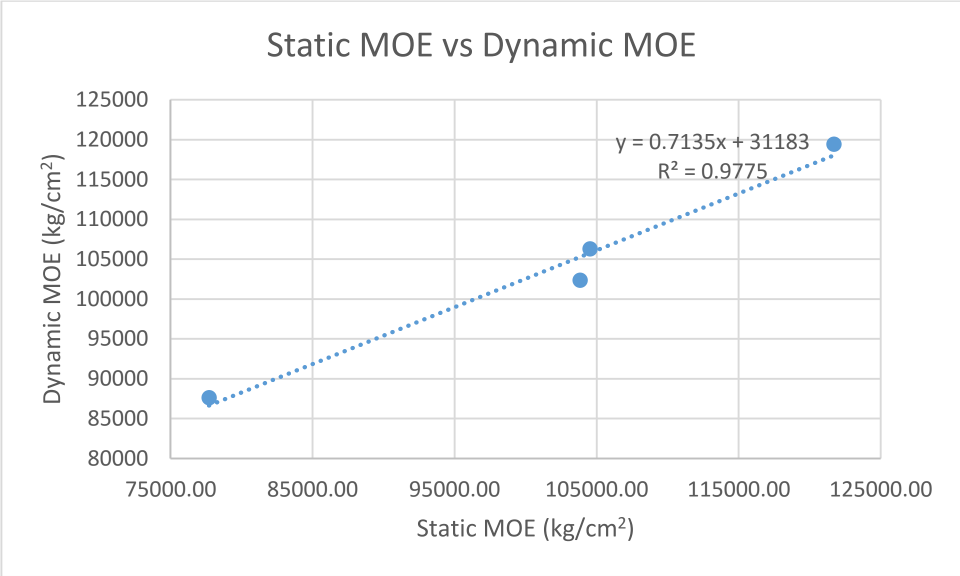


Fig. 9 Relationship between Static MOE and Dynamic MOE in the four 62-year old trees from Elival

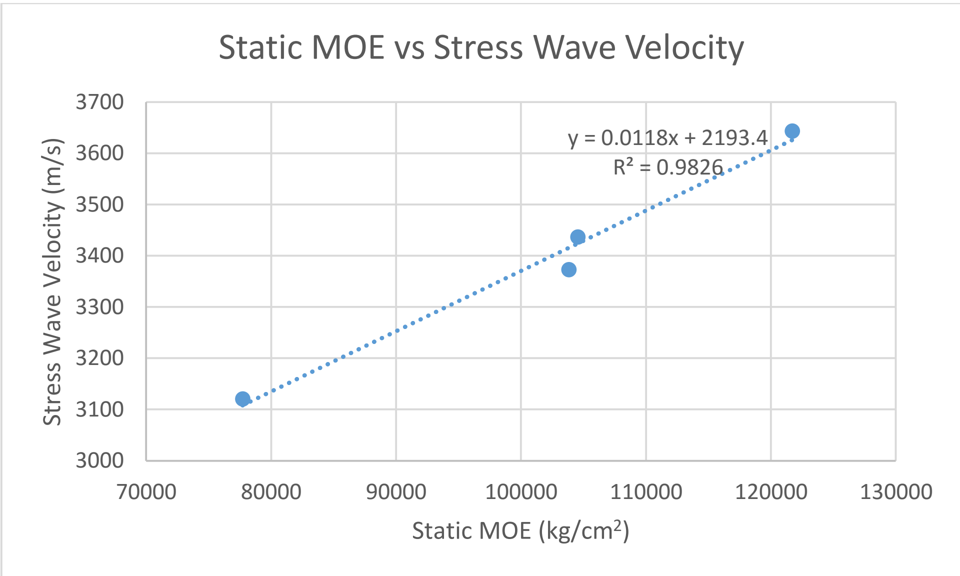


Fig. 10 Relationship between Static MOE and stress wave velocity in the four 62-year old trees from Elival.

4.5 GROWTH PROPERTIES

4.5.1 Girth at Breast Height (GBH)

In the three clonal trails analyzed, Girth at Breast Height was found to have significant difference only at the 13 year old clonal trail at Chettikkulam. Clone number T10 (59.25) was found to have higher mean GBH than any other clone followed by T46 (59.08). Clone number T6 (25.08) had the lowest GBH of them all (Table 17). In the 35 year old CSO at Walayar and 3 year old trail plot at Vellikulangara, the trait was found to have no significant difference between clones (Table 16 & 18).

4.5.2 Height

Height was found to have significant difference between clones in the 13 year old clonal trail at Chettikkulam only. Here, clone number T46 (13.27) had mean height greater than all other clones. Lowest mean height was exhibited by clone number T6 (7.47) (Table 17). In the 35 year old CSO at Walayar and 3 year old trail plot at Vellikulangara the trait was found to have no significant difference between clones (Table 16 & 18).

4.5.3 Bole Height

In the study Bole Height had significant difference between clones at the 13 year old clonal trail at Chettikulam but was found to have no significant difference between clones of 35 year old Clonal Seed Orchard at Walayar. At Chettikkulam, clone number T10 (7.33) was found to have highest mean Bole Height and clone number T6 (4.20) had the lowest (Table 17).

4.5.4 Number of Branches

Number of branches possessed by various clones was found to be significantly different at clonal trails at Chettikulam and Vellikulangara, the clones of which were of 13 and 3 years of age respectively. In the 35 year old CSO at Walayar the trait was found to have no significant difference between clones. At Chettikkulam, mean number of branches was highest for clone number T11 (19.50) and lowest for T6 (13.83) (Table 17).

Table 16. Mean and standard deviation for various growth traits of the twenty 35 year old clones at Walayar, Palakkad

Clone	GBH	Height	Bole Height	Number of Branches
KLS1	118.10	15.26	8.94	10
	(12.97)	(0.71)	(1.15)	(3)
KLS2	101.70	13.84	7.34	9
	(22.26)	(0.59)	(1.20)	(1)
KLS3	109.70	14.82	8.62	10
	(15.23)	(0.79)	(1.63)	(1)
KLS4	123.60	15.90	8.64	9
	(19.73)	(2.23)	(3.59)	(2)
KLN1	119.20	13.90	8.56	10
	(15.61)	(1.27)	(1.12)	(2)
KLN2	116.00	14.98	9.98	12
	(24.39)	(1.33)	(1.14)	(4)
KLN4	88.70	14.26	8.34	11
	(21.41)	(1.34)	(0.28)	(3)
KLK1	131.40	15.80	8.98	11
	(13.89)	(0.67)	(2.34)	(3)
KLK2	109.40	14.16	8.24	11
	(24.63)	(2.28)	(1.61)	(3)
TNT1	111.00	13.96	8.10	9
	(16.58)	(1.60)	(2.37)	(2)
TNT3	108.70	14.02	9.08	9
	(27.18)	(1.81)	(2.48)	(2)
TNT4	111.20	14.16	7.76	9
	(18.39)	(1.48)	(2.18)	(2)
TNT5	114.20	14.10	9.04	9
	(8.88)	(2.43)	(2.11)	(2)
TNT6	108.50	14.40	9.12	11
	(26.56)	(1.83)	(2.43)	(3)
TNT10	118.60	14.06	8.70	10
	(8.10)	(1.81)	(1.54)	(2)
TNT11	96.50	12.46	5.80	7
	(12.32)	(1.18)	(1.85)	(2)
TNT15	111.50	14.18	8.26	8
	(12.91)	(1.65)	(1.64)	(1)
TNT16	108.10	14.62	7.74	9
	(13.95)	(2.27)	(3.16)	(1)
TNT20	108.80	14.40	7.74	10
	(13.14)	(1.41)	(2.66)	(3)
SBL1	95.50	11.26	5.88	12
	(20.14)	(1.17)	(1.25)	(5)

Table 17. Mean and standard deviation for various growth traits of ten 13 year old teak clones at Chettikkulam, Trissure

	GBH	Height	Bole Height	No. of branches
T26	30.92 (5.71)	11.13 (1.04)	7.17 (0.48)	16 (1)
T21	39.33 (7.22)	11.72 (0.81)	6.97 (0.33)	16 (1)
T6	25.08 (2.91)	7.47 (0.59)	4.20 (0.91)	14 (2)
T5	27.75 (3.95)	10.40 (1.12)	5.97 (0.37)	17 (2)
T11	34.50 (3.82)	10.90 (0.88)	5.67 (0.65)	20 (1)
T27	27.16 (2.99)	11.06 (0.3)	5.76 (0.99)	16 (2)
T10	59.25 (13.28)	12.00 (1.41)	7.33 (0.8)	15 (1)
T46	59.08 (15.77)	13.27 (0.94)	7.20 (0.62)	15 (1)
T47	44.00 (9.01)	11.57 (1.09)	6.03 (0.47)	15 (2)
UK	34.97 (5.17)	11.23 (0.64)	6.53 (0.52)	15 (1)

Table 18. Mean and standard deviation for various growth traits of four 3 year old teak clones at Vellikulangara, Trissure

Clone	GBH	Height	Number of Branches
1	24.50 (3.21)	6.33 (0.09)	20 (3)
2	25.83 (0.75)	6.28 (0.1)	16 (2)
3	25.42 (2.97)	6.29 (0.08)	19 (1)
4	24.83 (3.86)	6.31 (0.06)	18 (2)

4.6 RELATIONSHIP BETWEEN WOOD PROPERTIES AND GROWTH TRAITS.

Growth traits was not found to have any significant correlation with basic density or dynamic modulus of elasticity at the 35 year old CSO at Walayar but Basic density and dMOE was found to have good correlation between each other (0.566) (Table 19).

At the 43 year old Seed Production Area (SPA) at Nilambur both basic density and Dynamic MOE were found to have no significant correlation with any of the growth traits studied (Table 20).

At Chettikkulam, for the studied traits basic density was found to have correlation only with Dynamic MOE while Dynamic MOE was found to have significant correlation with all traits studied except number of branches (Table 21).

Dynamic MOE was found to have significant correlation with GBH at the 3 year old trail at Vellikulangara. Here density didn’t have any significant correlation with any of the traits under investigation (Table 22).

Table 19. Correlations between the various characteristics studied in the twenty 35 year old teak clones at Walayar, Palakkad

	GBH	Height	Number of Branches	Density	dMOE
GBH	1				
Height	0.568**	1			
Number of branches	0.302**	0.335**	1		
Density	-0.163	-0.143	-0.101	1	
dMOE	-0.080	-0.052	-0.013	0.566**	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 20. Correlations between the various characteristics studied in the 43 year old teak trees at Nilambur, Malappuram

	girth	height	Bole height	Number of branches	density	dMOE
Girth	1					
Height	0.513**	1				
Bole height	0.377**	0.685**	1			
No. of Branches	- 0.046	0.048	0.182	1		
Density	0.012	0.064	0.066	- 0.078	1	
dMOE	- 0.074	-0.101	0.061	- 0.036	- 0.171	1

**. Correlation is significant at the 0.01 level.

Table 21. Correlations between the various characteristics studied in the ten 13 year old teek clones at Chettikkulam, Trissure

	GBH	Height	Bole Height	No. of Branches	Density	dMOE
GBH	1					
Height	0.714**	1				
Bole Height	0.569**	0.794**	1			
No. of Branches	-0.140	0.154	-0.018	1		
Density	-0.021	0.174	0.115	0.056	1	
dMOE	0.500**	0.622**	0.452**	0.034	0.341**	1

**. Correlation is significant at the 0.01 level (2-tailed).

Table 22. Correlations between the various characteristics studied in the four 3 year old teak clones at Vellikulangara, Trissure

	GBH	Height	Number of Branches	Density	dMoE
GBH	1				
Height	-0.038	1			
No. of Branches	0.048	0.074	1		
Density	-0.177	0.313	0.157	1	
dMoE	0.527**	0.361	0.052	-0.011	1

**. Correlation is significant at the 0.01 level (2-tailed).

4.7 GENETIC VARIATIONS

4.7.1 Broad Sense Heritability (H^2)

In the 20 clones of the 35 year old CSO at Walayar the intrinsic characters like density (derived from PPD) and Dynamic MoE (derived from velocity) was found to have high heritability at broad sense with values of (0.66) and (0.68) respectively. PPD and SWV also had high value for H^2 here of (0.65) and (0.69) respectively. H^2 values for all other characters was comparatively very less in this matured plantation at Walayar (Fig. 11).

In the Chettikulam plantation all the traits showed moderate to high values for H^2 with Height and GBH having the highest values (0.70 and 0.68 respectively). Here basic density obtained by laboratory analysis had an H^2 value of (0.29) and the PPD had an H^2 value of (0.41). H^2 for dMoE was (0.34) and for velocity was (0.36) (Fig. 12).

In the younger trial at Vellikulangara, only, number of branches per tree had moderate H^2 value (0.39), and density showed an H^2 value of (0.20) (Fig. 13).

Broad sense Heritability was found to increase with age in the intrinsic characters and for other traits it was found to increase in the 13 year old stand than the 3 year old stand but decreased in the more mature 35 year old stand.

4.7.2 Genetic Gain

At Walayar, Velocity, Density and Dynamic MOE was found to have greater genetic gain, when compared to growth traits (Fig. 14). At Chettikkulam, GBH had the greatest genetic gain (Fig. 15). In genetic gain also, an age wise trend was observed only in intrinsic characteristics. At Vellikulangara all characters showed very less Genetic gain values (Fig. 16).

Table 23. Analysis of variance for growth and wood traits measurements of twenty 35 year old teak clones at Walayar, Palakkad

		Sum of Squares	Degree of freedom	Mean Square	F	Sig.
Girth	Between Groups	9222.86	19	485.414	1.454	0.126
	Within Groups	26700.10	80	333.751		
	Total	35922.96	99			
Height	Between Groups	99.13	19	5.217	2.071	0.013
	Within Groups	201.51	80	2.519		
	Total	300.64	99			
Bole height	Between Groups	99.49	19	5.236	1.262	0.233
	Within Groups	332.02	80	4.150		
	Total	431.51	99			
No. of Branches	Between Groups	155.96	19	8.208	1.281	0.220
	Within Groups	512.80	80	6.410		
	Total	668.76	99			
PPD	Between Groups	117.98	19	6.210	10.694	0.000
	Within Groups	46.45	80	0.581		
	Total	164.44	99			
Velocity	Between Groups	3009184.10	19	158378.110	11.955	0.000
	Within Groups	1059795.21	80	13247.440		
	Total	4068979.31	99			
Density	Between Groups	52030.58	19	2738.452	10.694	0.000
	Within Groups	20486.78	80	256.085		
	Total	72517.36	99			
dMOE	Between Groups	103223754.53	19	5432829.186	16.127	0.000
	Within Groups	26950875.58	80	336885.945		
	Total	130174630.10	99			

Table 24. Analysis of variance for growth and wood traits measurements of ten 13 year old teak clones at Chettikkulam, Trissure

		Sum of Squares	Degree of freedom	Mean Square	F	Sig.
GBH	Between Groups	8367.850	9	929.761	13.972	0.000
	Within Groups	3327.250	50	66.545		
	Total	11695.100	59			
Height	Between Groups	119.084	9	13.232	15.213	0.000
	Within Groups	43.488	50	0.870		
	Total	162.573	59			
Bole Height	Between Groups	50.417	9	5.602	13.195	0.000
	Within Groups	21.227	50	0.425		
	Total	71.643	59			

Number of branches	Between Groups	121.733	9	13.526	5.469	0.000
	Within Groups	123.667	50	2.473		
	Total	245.400	59			
PPD	Between Groups	47.143	9	5.238	5.248	0.000
	Within Groups	49.905	50	0.998		
	Total	97.048	59			
Density	Between Groups	20085.530	9	2231.726	5.248	0.000
	Within Groups	21262.069	50	425.241		
	Total	41347.599	59			
Velocity	Between Groups	948096.257	9	105344.029	4.335	0.000
	Within Groups	1214964.842	50	24299.297		
	Total	2163061.099	59			
MOE	Between Groups	17707374.313	9	1967486.035	3.484	0.002
	Within Groups	28234551.905	50	564691.038		
	Total	45941926.217	59			

Table 25. Analysis of variance for growth and wood traits measurements of four 3 year old teak clones at Vellikulangara, Trissure

		Sum of Squares	Degree of freedom	Mean Square	F	Sig.
GBH	Between Groups	6.365	3	2.122	.245	0.864
	Within Groups	172.875	20	8.644		
	Total	179.240	23			
Height	Between Groups	0.006	3	0.002	.307	0.820
	Within Groups	0.135	20	0.007		
	Total	0.142	23			
Number of Branches	Between Groups	50.792	3	16.931	4.896	0.010
	Within Groups	69.167	20	3.458		
	Total	119.958	23			
PPD	Between Groups	3.395	3	1.132	2.533	0.086
	Within Groups	8.935	20	0.447		
	Total	12.330	23			
Velocity	Between Groups	115815.864	3	38605.288	1.796	0.180
	Within Groups	429867.317	20	21493.366		
	Total	545683.182	23			
Density	Between Groups	1446.265	3	482.088	2.533	0.086
	Within Groups	3806.765	20	190.338		
	Total	5253.030	23			
MOE	Between Groups	1299647.617	3	433215.872	1.070	0.384
	Within Groups	8096890.064	20	404844.503		
	Total	9396537.681	23			

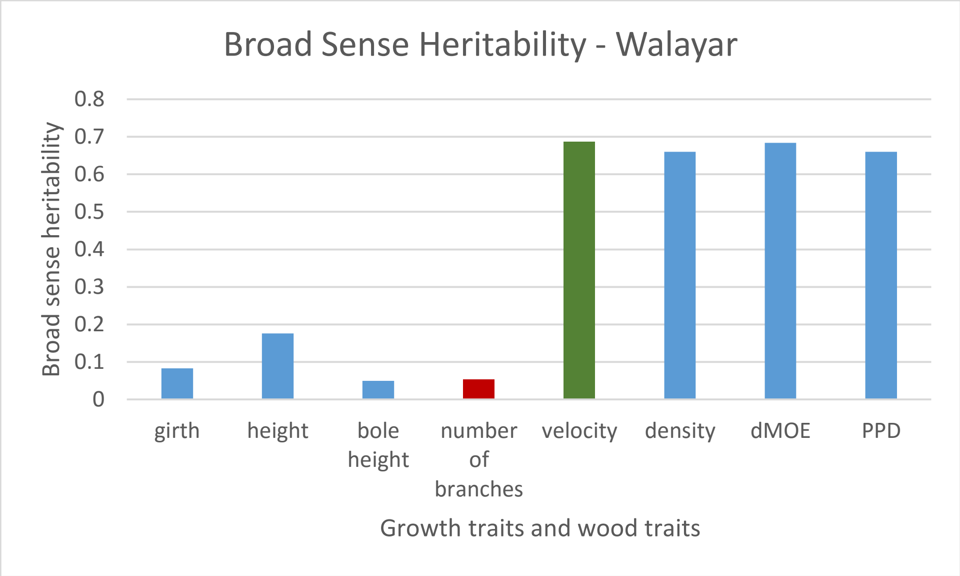


Fig. 11 Broad Sense Heritability of various traits for twenty 35-year old clones at Walayar

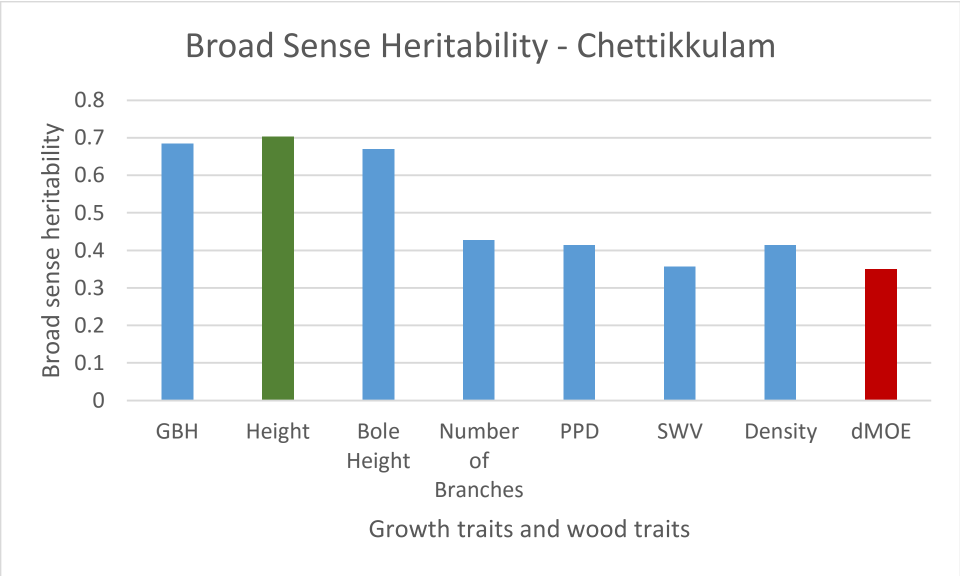


Fig. 12 Broad Sense Heritability of various traits for ten 13-year old clones at Chettikkulam

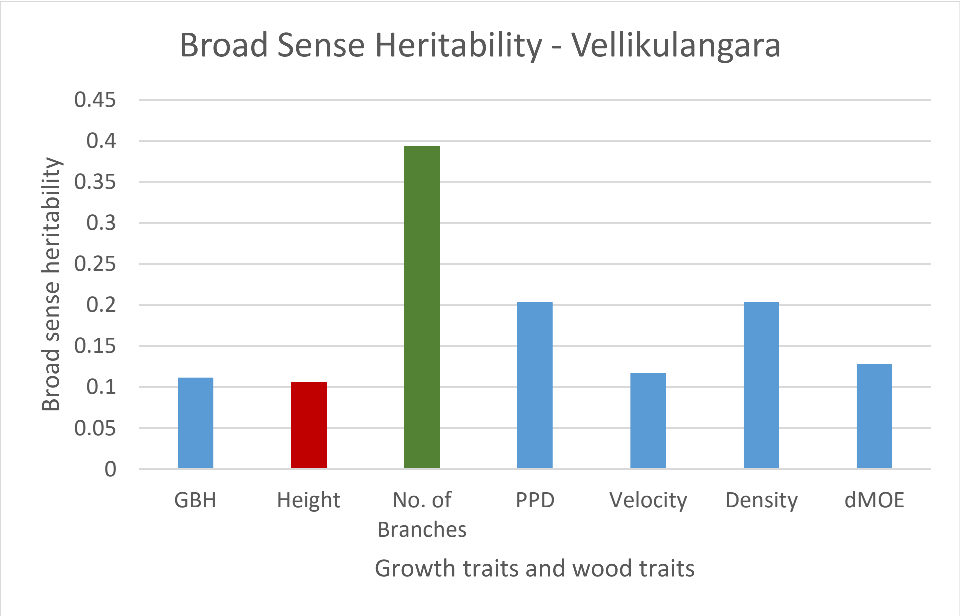


Fig. 13 Broad Sense Heritability of various traits for four 3-year old clones at Vellikulangara.

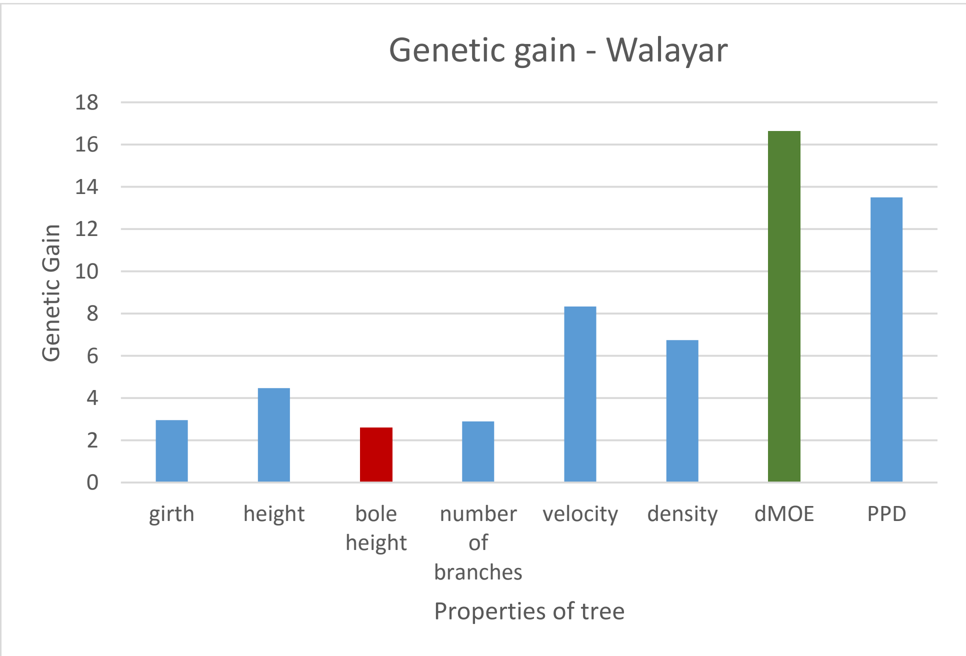


Fig. 14 Genetic Gain for various traits in twenty 35-year old clones at Walayar

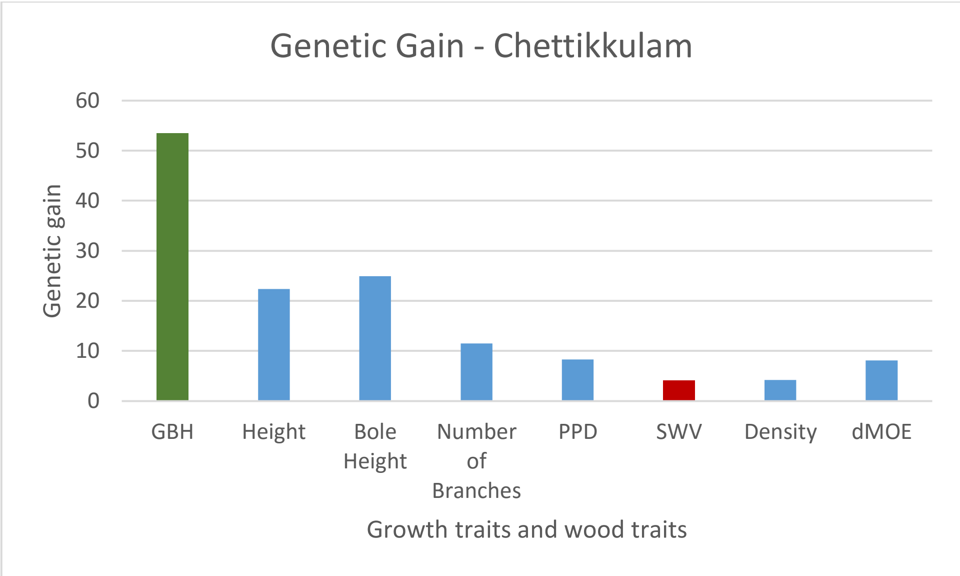


Fig. 15 Genetic Gain for various traits in ten 13-year old clones at Chettikkulam

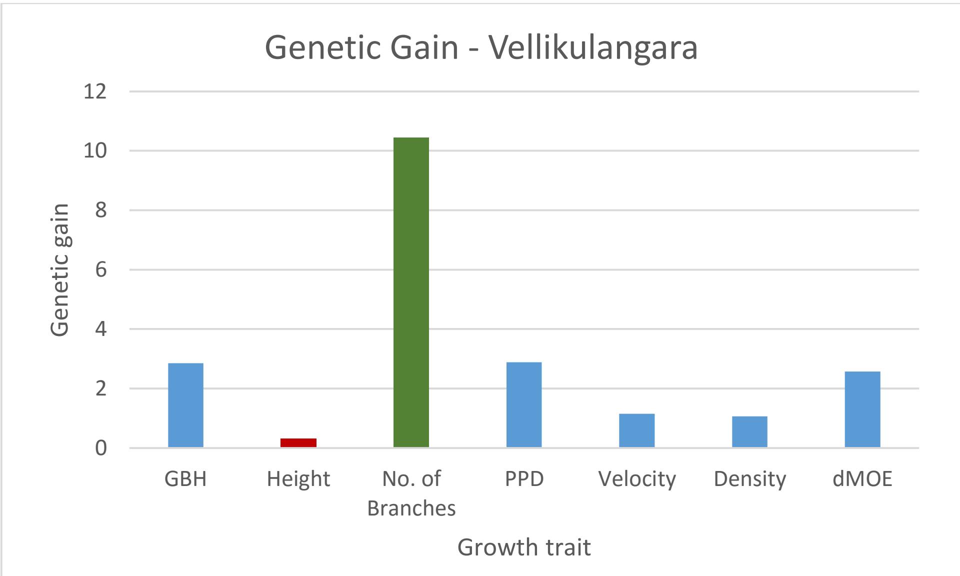


Fig. 16 Genetic Gain for various traits at Vellikulangara

Table 26. Estimated genetic parameters of various characters in the 35 year old teak clones at Walayar, Palakkad

Traits	Mean	Genetic Variance	Environmental Variance	Phenotypic Variance	Broad sense heritability	Genetic Advance	Genetic gain
Girth	110.52	30.33	333.75	364.08	0.08	3.27	2.96
Height	14.23	0.54	2.52	3.06	0.18	0.64	4.47
Bole Height	8.24	0.22	4.15	4.37	0.05	0.21	2.60
No. of Branches	9.82	0.36	6.41	6.77	0.05	0.28	2.90
Velocity	3488.86	29026.13	13247.44	42273.57	0.69	290.82	8.34
Density	552.26	496.47	256.09	752.56	0.66	37.28	6.75
dMOE	10.9916	1.15	0.53	1.68	0.68	1.83	16.64
PPD	13.15	1.13	0.58	1.71	0.66	1.78	13.50

Table 27. Estimated genetic parameters of various characters in the 13 year old teak clones at Chettikkulam, Trissure

Traits	Mean	Genotypic variance	Environmental variance	Phenotypic variance	Broad sense heritability	Genetic advance	Genetic gain
GBH	38.20	143.86	66.55	210.41	0.68	20.43	53.49
Height	11.07	2.06	0.87	2.93	0.70	2.48	22.40
Bole Height	6.28	0.86	0.43	1.29	0.67	1.57	24.94
No. of Branches	15.90	1.84	2.47	4.32	0.43	1.83	11.49
SWV	3444.73	13507.46	24299.30	37806.75	0.36	143.12	4.15
Density	546.02	301.08	425.24	726.32	0.41	23.01	4.21
dMOE	10.71	0.51	0.95	1.46	0.35	0.87	8.11
PPD	13.46	0.71	1.00	1.70	0.41	1.11	8.28

Table 28. Estimated genetic parameters of various characters in the 3 year old teak clones at vellikkulangara, Trissure

Traits	Mean	Genetic variation	Environmental variation	Phenotypic variation	Broad sense heritability	Genetic advance	Genetic gain
GBH	25.15	1.09	8.64	9.73	0.11	0.72	2.85
Height	6.30	0.00	0.01	0.01	0.11	0.02	0.31
No. of Branches	18.54	2.25	3.46	5.70	0.39	1.94	10.45
PPD	10.90	0.11	0.45	0.56	0.20	0.31	2.88
Velocity	3257.94	2851.99	21493.37	24345.35	0.12	37.65	1.16
Density	607.85	48.63	190.34	238.96	0.20	6.48	1.07
dMOE	9.57	0.11	0.76	0.87	0.13	0.25	2.57

4.7.3 Cluster analysis and clone selection

Based on the four main characters studied (i.e. GBH, Height, Wood Basic Density and SWV) five clusters were identified for the clones at Walayar (Fig. 17) and four clusters for the clones at Chettikkulam (Fig. 18).

With respect to wood traits, cluster number 3 was found to have the best performing clones (Table 29) in walayar; it included two clones (TNT 16 and KLN 1) which had significantly high values for wood properties with respect to clones from other clusters, mean values of these trait was also high for this cluster. Cluster number 5 was recognised as the second best cluster from Walayar which included six clones. It had the second highest values for mean density and mean SWV with respect to clusters (Table 29).

Similarly Cluster number 2 was identified as the best performing cluster in the Chettikkulam trial (Table 30). It included two clones (T47 and T46) which was found to have better values for the important traits studied. Second best performing cluster in Chettikkulam was cluster number 1, and it included 4 clones.

In the other fields clustering analysis was not done as, in Vellikulangara it included only very few number of clones and in Nilambur the trees was classified based on girth class.

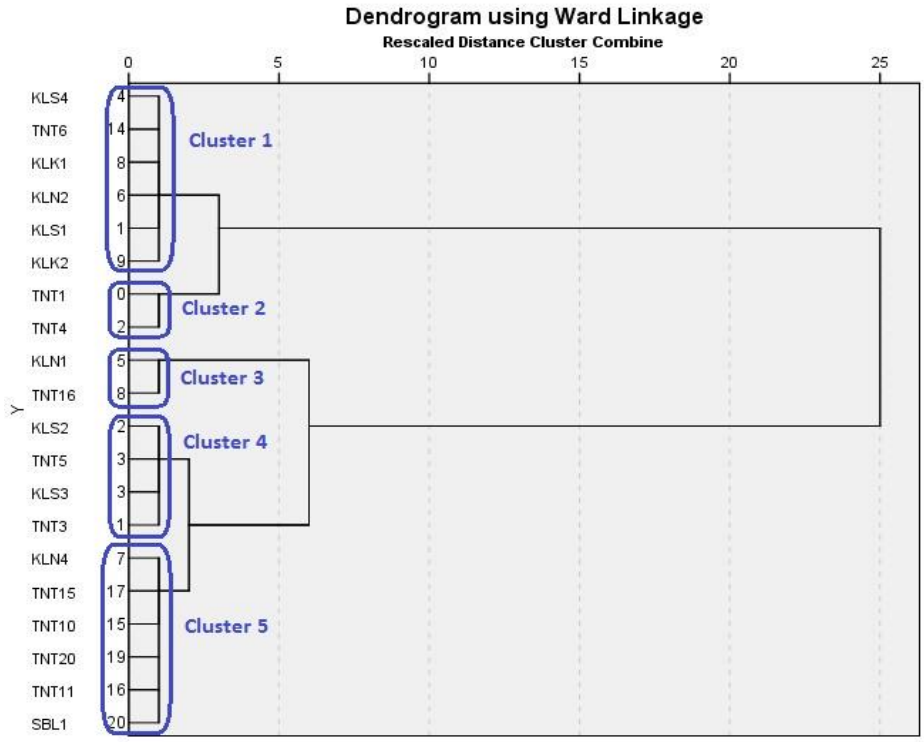


Fig. 17 Dendrogram showing Hierarchical cluster analysis for twenty 35 year old clones at Walayar

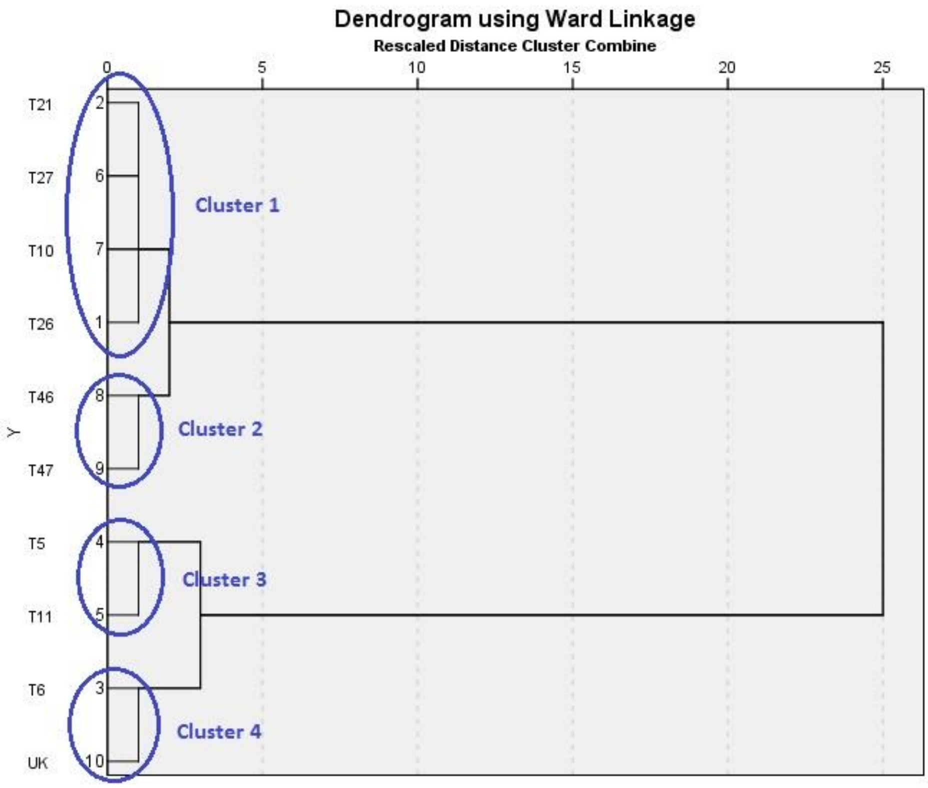


Fig. 18 Dendrogram showing Hierarchical cluster analysis for ten 13 year old clones at Chettikkulam

Table 29. Cluster means for 5 different clusters identified for twenty 35 year old Teak clones at Walayar, Palakkad

Cluster no.	No. of clones	Mean GBH (cm)	Mean Height (m)	Mean Density (Kg m^{-3})	Mean Velocity (m s^{-2})
1	6	117.83	15.08	531.60	3352.01
2	2	111.10	14.06	540.12	3194.08
3	2	113.65	14.26	592.22	3808.54
4	4	108.58	14.20	553.57	3502.09
5	6	103.27	13.44	562.78	3608.62

Table 30. Cluster means for 4 different clusters identified for ten 13 year old Teak clones at Chettikkulam, Trissure

Cluster no.	No. of clones	Mean GBH (cm)	Mean Height (m)	Mean Density (Kg m^{-3})	Mean Velocity (m s^{-2})
1	4	39.17	11.48	550.77	3513.39
2	2	51.54	12.42	548.19	3587.82
3	2	31.13	10.65	530.82	3362.56
4	2	30.00	9.35	549.57	3246.51

DISCUSSION

The present investigation envisages a detailed investigation of the physical and mechanical properties of teak (*Tectona grandis* L.f.), using destructive and non-destructive methods. The relationship of wood properties with various growth traits and between each other were also analysed and the genetic characteristics of these traits were determined. The study also aimed at evaluating the suitability of non-destructive techniques (NDT) and semi-destructive techniques (SDT) as predictors of timber properties under field conditions.

5.1 APPLICATION OF NON DESTRUCTIVE TESTING METHODS

5.1.1 Pilodyn Penetration Depth

In the present study, Pilodyn penetration depth was found to be negatively correlated with basic density in 44 trees studied in the clonal trail plot at Chettikkulam with a correlation coefficient of (-0.642). Mean PPD values of the clones were also found to be negatively correlated with the mean basic density values of the same clones with a correlation coefficient of (-0.755) Furterh, regression analysis was also carried between the two traits and a regression equation was derrived. From the results it could be established that PPD values can be used to estimate basic density in standing trees.

A similar study by Kien and others (2007)in progeny trials of *Eucalyptus urophylla* in northern Vietnam at the age of eight and nine years estimated genetic correlation between pilodyn penetration and wood density and reported a correlation coefficient of -0.86. Wu et al. (2010) also tested the effectiveness of pilodyn in evaluating wood properties including basic density. Strong negative correlations were found between pilodyn penetration and wood properties, and the coefficients ranged from -0.433 to -0.755 in their study. The results confirmed that pilodyn is an effective and efficient means of estimating wood properties like wood basic density. In the study by Dhanya (2012) significant negative correlation (1% level) was noticed between specific gravity (oven dry) and pilodyn penetration depth in different tropical hard wood species including teak. They reported the highest correlation in Teak (-0.907).

5.1.2 Stress Wave Velocity

Stress Wave Velocity was found to have significant correlation with static MoE (0.991), Modulus of rupture (0.974) and horizontal shear stress at maximum load (0.973). In similar studies, Mochan et al., (2009) also found that there is a very strong relationship (R2>0.9) between dynamic modulus of elasticity and its static equivalent for small, defect-free samples and sawn timber. This formed the basis for using acoustic machines for in-line grading of sawn timber. In a-addition, these results indicated that portable resonance-based tools can be used to predict the mechanical properties of large-section timber and poles which would otherwise only be visually inspected. Searles and Moore (2009) found that, portable stress-wave based tools provide a cost effective means for predicting the stiffness of the resource, either in standing tree or in log form. In the application of stress-wave-based tools to the Sitka spruce supply chain in the UK, there was a strong relationship between the mean modulus of elasticity of the timber cut from a site and the average stress wave velocity measured on trees at the site (R^2=0.76).

5.2 GENETIC VARIATION AMONG THE GROWTH AND WOOD PROPERTIES

5.2.1 Wood Basic Density and Dynamic MOE

Wood density is influenced by cell wall thickness, the proportion of different kind of tissues, and the percentage of lignin, cellulose and extractives (Valente et al., 1992). It is considered the best single index of wood quality because it is the most dependable characteristic for predicting timber strength (Shirin et al., 1998). It correlates with numerous morphological, mechanical, physiological, and ecological properties (Jerome et al., 2006). It affects various products of wood, such as pulp and paper properties, wood strength, and wood quality (Zobel and van Buijtenen, 1989). It has been a desirable trait to include in tree improvement programs because of its economic value and high degree of genetic control (Sprague et al., 1983).

Basic density was assessed using a core taken near breast height, which seems to be highly correlated with the whole tree values for the character by several workers (Lausberg et al., 1995; Raymond and Muneri, 2001; Kube and Raymond, 2002). In the present study, wood basic density estimated using the cores taken from breast height of the trees significantly differed between clones in the 13 year old trees at Chettikkulam. The mean basic density was found to be highest for the clone marked as UK (589.83 kg/m^3) and the lowest mean specific gravity was found for clone T5 (522.33 kg/m^3) (Fig. 7). The variation in the specific gravity among the clones may be due to differences in the cell wall thickness, the proportion of different kind of tissues and the percentage of lignin, cellulose and extractives. This may be an indication of the fact that specific gravity is a highly heritable trait in trees. In the present study, basic density obtained by laboratory analysis for teak had an H^2 value of (0.29) which may be considered a moderate value though it is less compared to the study by Wei and Borralho (1997) in *Eucalyptus urophylla* where, results showed that basic density is under strong genetic control, with heritability of 0.71. Similarly, Lan (2011) found that *Eucalyptus urophylla* wood properties were under moderate to strong additive genetic control (H^2 = 0.35-0.66). A study in *Eucalyptus globulus* by Muneri and Raymond (2000) found that wood density had very large provenance differences together with high heritability (H^2 of 0.67 to 1). Kien and others (2007) studied genetic parameters for wood basic density in two thinned open pollinated progeny trials of *Eucalyptus urophylla* in northern Vietnam at the age of eight and nine years, and the estimated narrow sense individual tree heritability (H^2) for wood basic density was 0.60. The lower heritability value obtained in Chettikkulam may be due to younger age of trees or the small number of samples taken for each clone.

The H^2 value of basic density derived from PPD and Dynamic MOE estimated using Stress Wave Velocity (SWV) was found to be high in the 35 year old trees at Walayar. Here, H^2 value for basic density and dynamic MOE were 0.66 and 0.68 respectively. In the 13 year old trial at Chettikkulam, dynamic MOE had a heritability of 0.34, the values being more similar to other studies.

Stiffness is the major basis of machine stress grading of sawn timber, and has a major influence on price. It is not a parameter that is readily measured in logs or standing trees. Derivation of a surrogate indicator for stiffness would facilitate more effective planning and permit effective log sorting, while also providing a valuable tool for breeders and silviculturists working with standing trees (Dickson et al., 2004). Wood stiffness was found to have H^2 value of 0.57 in a study of open pollinated 8 year old *E. grandis* trees by Santos and coworkers (2004). In another study by Sotelo Montes et al.,(2007) in open pollinated *Calycophyllum Spruceanum* of 3.3 years H^2 for stiffness was 0.47 for strength. Henson and co-workers (2004) reported H^2 as 0.57 in a 9 years old *E. dunnii* plantation.

In the three plantations of three different ages studied, it was noted that the readings from younger plantations was less stable and unreliable compared to the mature plantation. Constant heritability values was observed for the wood characters in most of the trials, while growth traits showed high values of heritability in immature stands, whereas very low values in mature stands. Similar age related trends were observed in other works as well; Shukla and co-workers (2007) assessed the physical and mechanical properties of timber of plantation grown *Acacia auriculiformis* A.Cunn. ex Benth. of 8, 12 and 13 year old trees from Sirsi, Karnataka, India. They found that timber of the 13 year old trees was dense, very strong, moderately tough, and stable in service and hard indicating that with age, more changes will happen and early estimations should be done carefully. Parolin and Ferriera (1998) stated that tree age is another factor which influences specific gravity. They also found that along with increase in tree age specific gravity also increased from 0.47 to 0.56 in the case of *Acacia mangium*. From the above foregoing, we can infer that most of the growth trait behaviours keep on changing with age and hence early estimation using this characteristics may not be desirable.

Zsuffa 1975 states, H^2 can be used to forecast genetic gain in clonal propagation. The reliability of such estimates depends on minimizing environmental differences between and within clones. In this study velocity, density and dynamic MOE were found to have greater genetic gain of 32.23%, 20.23%, 16.39% and 40.38% respectively than other growth traits at Walayar. At Chettikkulam, GBH had the greatest genetic gain of 126%. In genetic gain also, consistency in values was observed only in intrinsic characteristics.

5.2.2 Growth Traits

In the Chettikulam plantation all the traits showed moderate to high values for H^2 with Height and GBH having the highest values (0.70 and 0.68 respectively). This is against the usual trend of low heritability expressed in this traits, but in the other trials, very low H^2 values for these traits were observed.. For GBH H^2 values were 0.1and 0.08 and for height it was 0.1 and 0.18 at Vellikulangara and Walayar respectively. Supporting this trend was the study by Lan (2011) who found that, in *Eucalyptus urophylla* progeny trials, growth traits (H^2 = 0.05-0.39) were having low to moderate additive genetic control. A study in *Eucalyptus globulus* by Muneri and Raymond (2000) found similar patterns of genetic variation for diameter. For diameter there was relatively little difference amongst the provenances and a low heritability (H^2 of 0.16 to 0.33) was reported. The high values for H^2 for height and GBH observed in our study may be because of the lower age of the clones. Similarly, Callister and Collins (2008) analysed data from a 3.5-year-old teak progeny test with clonal replication located in northern Australia and found narrow-sense heritability to be 0.22 for diameter and 0.18 for height and broad-sense heritability to be 0.37 for diameter and 0.28 for height. Dickson and co-workers (2002) states that, the age at which each wood property may be reliably assessed so as to predict values at harvest, is important. Decisions about when and how to evaluate different wood properties must be based on the patterns of change over time and the accuracy of the assessment method. For many wood properties there is little information available about patterns of change with respect to increasing age, so it is not possible to suggest ages for assessment.

5.2.3 Non-Destructive Measurements - Pilodyn Penetration Depth and Stress Wave Velocity

Pilodyn penetration depth and stress wave velocity were found to be significantly different between clones in the 35-year-old CSO at Walayar and the 13-year-old tral at Chettikulam. At Walayar, PPD and SWV had H^2 values of 0.65 and 0.69 respectively and in the 13-year-old trial it was 0.41 and 0.36 respectively. In similar studies, Wei and Borralho (1997) states in *Eucalyptus* *urophylla* progeny trials in south east China, Pilodyn penetration was under strong genetic control with heritability of 0.64. Furthermore, Kien and coworkers (2007) states that in open pollinated progeny trials of *Eucalyptus urophylla* in northern Vietnam at the age of eight and nine years, H^2 value for pilodyn penetration was 0.42. In the study by Hidayati and others (2013), broad-sense heritability of growth, SWV, and Pilodyn Penetration were moderate. Eckard (2007) assessed the efficiency of the treesonic time-of-flight acoustic tool in screening young clones of loblolly pine for three economically important solid wood properties and found that SWV was highly efficient at selecting clones for MOE, moderate for MOR and poor for density.

5.3 RELATIONSHIP OF BASIC DENSITY AND DYNAMIC MOE WITH GROWTH TRAITS

In the 43 year old trees of the Seed Production Area (SPA) at Nilambur both basic density and Dynamic MOE were found to have no significant correlation with any of the growth traits studied. No character was found to have any significant correlation with basic density or dynamic modulus of elasticity at the 35 year old CSO at Walayar, but Basic density and dMOE were found to have good correlation between each other. So we can say in general that Basic Density and Dynamic MOE are not related to growth traits in Teak. Similar to this, was the study by Kien and others (2007) on progeny trials of *Eucalyptus urophylla* in northern Vietnam at the age of eight and nine years, wherein, the estimated genetic correlations among wood basic density and diameter at breast height, height, stem straightness and branch size at each site were weak.

Density seems to influence machinability, conversion, strength, paper yield and many other properties (Wimmer at al., 2002). Most mechanical properties of wood are closely related to specific gravity and density (Walker, 1993; Haygreen and Bowyer, 1996). Jerome et al. (2006) reported that wood density is the single best descriptor of wood; it correlates with many morphological, mechanical, physiological and ecological properties.

The segregation of trees and logs has often been made on the basis of external characteristics. While this generally provides valuable information on the volume of timber that can be recovered, it is not a good indicator of the mechanical properties of the timber (Wagner et al, 2003). In this context, it is pertinent to mention the study by Jun Lan (2011) in which he found that, there was no significant relationship between growth traits and wood properties (Pilodyn penetration, basic density or acoustic velocity squared). This proves that growth traits based selection can lead to plantations with uncertain physical and mechanical qualities in teak.

5.4 CLUSTERING AND SELECTION OF CLONES

Using hierarchical clustering analysis by Ward's method, the clones in Walayar CSO and Chettikkulam were grouped into various clusters with respect to the four important traits namely girth, height, wood basic density and stress wave velocity. Clusters were formed with closely related clones coming in the same clusters thereby making it possible to select clusters with trees having the desired characters according to the breeder's needs. If the end use requirement is for a better timber quality, the clusters with higher mean value for wood basic density and velocity can be selected, and for better volume production, clusters with high values of mean girth and height can be selected. Similar selection procedure was used by Kumar and Gurumurthi (1997) who selected the fastest growing male and female clones of *Casuarina equisetifolia* following the method of hierarchical cluster analysis adopted in this study.

5.5 CONCLUSION

Using the non-destructive testing methods wood properties of standing trees could be successfully analysed, which up to very recent times was analysed only by destructive means leading to felling of trees. The readings obtained by these instruments was useful in analysing the genetic divergence of these wood traits in Teak, and the heritability values obtained revealed the importance of understanding these traits especially with respect to selection of clones for tree improvement programmes.

SUMMARY

Teak trees at four tree improvement trial locations viz., Walayar (CSO), clonal trials at Chettikkulam and Vellikulangara and Nilambur (SPA) in Kerala were studied to understand the variation in wood physical and mechanical wood properties using non-destructive testing (NDT) methods using Pilodyn and Tree sonic timer to evaluate its suitability in predicting actual timber properties under field conditions. The relationship of wood properties with growth traits was also analysed.

To elicit the relationship between NDT parameters and actual physical, and mechanical properties, trees were sampled using destructive means in a mature teak plantations at Elival, Palakkad. An attempt was also made to understand the genetic variation in the various properties estimated. The salient findings of the study are listed below.

- Teak clones were significantly different with respect to wood characters like basic density and modulus of elasticity (MOE) in the clones studied and these properties had high broad sense heritability values in the same, especially in matured plantations. Basic density and MOE were found to have moderate values of genetic gain as well in the clones studied.

- Growth traits like GBH, height, bole height and number of branches was found to have low broad sense heritability in the teak clones evaluated.

- Estimated broad sense heritability values tends to increase with age for the clonal teak plantations studied for density and dynamic MOE and tends to decrease with age for growth traits like height and GBH.

- Pilodyn pin penetration depth (PPD) was found to be significantly different between clones in both 35 year old plantation at Walayar and 13 year old plantation at Chettikkulam; in both trials the traits proved to have good heritability as well, accounting to H^2 values of 0.65 and 0.41 respectively.

- Stress wave velocity (SWV) was found to be significantly different between clones in both 35 year old plantation at Walayar and 13 year old plantation at Chettikkulam; in both trials, the traits proved to have good heritability, accounting H^2 values of 0.69 and 0.36 respectively.

- Wood basic density was found to have significant negative correlation with PPD in the forty four 13-years old trees studied at Chettikkulam. The correlation coefficient obtained was -0.64. Mean PPD value of clones was also found to be negatively correlated with the mean basic density values of the same clones with a correlation coefficient of -0.75.

- Regression analysis was also conducted for basic density and PPD, and a regression equation was derived. From the results, it was found that PPD values can be used to estimate basic density of standing trees.

- Stress wave velocity was found to have significant correlation with Static MoE ($r = 0.991$), modulus of rupture ($r = 0.974$) and horizontal shear stress at maximum load ($r = 0.973$) and many other mechanical properties estimated in the four tree logs obtained from Elival forest section.

- Basic density and dynamic MOE was not found to have any significant correlation with the growth traits like GBH, height, bole height and number of branches in teak trees. Hence, breeding for growth traits alone can negatively affect the wood characters of the trees in the trials.

- Basic density and dynamic MOE was found to be correlated with each other at Walayar and Chettikkulam with a correlation coefficient of 0.56 and 0.34. Similar results were obtained for most of the growth traits which were however found to be significantly correlated with each other.

- PPD was found to vary within the individual trees as well, at the pith, middle and periphery positions of the discs obtained from the felled trees from Elival wherein it was found that PPD values vary at these three positions along the same direction.

- PPD values from the periphery of the logs and discs was found to have significant correlation with the PPD values from the middle position of the same logs and discs.

- Using hierarchical clustering analysis by Ward's method, cluster groups of closely related clones with respect to wood and growth properties could be sorted successfully. These clusters can possibly be further used for selecting superior clones for the desired traits.

It can be concluded from the study that both basic density and modulus of elasticity possess high degree of genetic variation, and has better broad sense heritability in Teak clones studied compared to growth traits which are the only parameters usually used in tree selection programmes for breeding. It was also observed that there is no relationship between growth traits and the intrinsic characters. So it is important to estimate basic density and modulus of elasticity in trees during selection for breeding along with growth traits.

The non-destructive instruments deployed such as Pilodyn and Tree Sonic Timer can be successfully put into use for meeting this purpose since their reliability has been proven in predicting wood traits in standing trees based on the results of this study.

REFERENCE

Amishev, D. and Murphy, G.E. 2008. In-forest assessment of veneer grade Douglas-fir logs based on acoustic measurement of wood stiffness. Forest Products. J., 58 (11): 42–47.

Ayarkwa, J., Hiroshima, Y. and Sasaki, Y. 2001. Predicting modulus of rupture of solid and finger jointed tropical African hardwoods using longitudinal vibration. Forest Products J., 51(1): 85-92.

Barefoot, A.C., Hitchlings, R.G., Ellwood, E.L. and Wilson, E. 1970. The relationship between loblolly pine fiber morphology and kraft paper properties. Technical Bulletin 202, North Corolina Agricultural Experiment Station, Raleigh, USA, 88p.

Beaudoin, M., Masanga, B.O., Poliquin, J. and Beauregard, R.L. 1989. Physical and mechanical properties of plantation grown tamarack. Forest Products J., 39(6): 510-515.

Bhat, K.M., Damodaran, K., Aswanthanarayana, B.S., Prasad, T.R.N. and Shyamsundar, K. 1999. Properties and utilisation of small timber resource of teak platations. Proceedings of National Seminar on Processing and Utilization of Plantation timbers and Bamboo, 15th October, 1999 (eds. Narayanaswamy, R.V. and Reddy, G.K.) IPIRTI, Banglore, India. pp. 255-261.

Bowyer, J.L. and Smith, R.L. 1998. The nature of wood and wood products. CD-ROM, University of Minnesota, Forest Products Management Development Institute, St. Paul, Minnesota, USA.

Callister, A.N. and S. Collins 2008. Genetic parameter estimates in a clonally replicated progeny test of teak (*Tectonagrandis* Linn. f.). Tree Genetics and Genomes 4:237-245

Chauhan, S.S. and Walker, J.C.F. 2006. Variations in acoustic velocity and density with age, and their interrelationships in radiata pine. For. Ecol. Manage., 229 (1-3): 388-394.

Chauhan, S.S., Entwistle, K.M. and Walker, J.C.F. 2005. Differences in acoustic velocity by resonance and transit-time methods in an anisotropic laminated wood medium. Holzforschung, 59: 428-434.

Chih-Lin, H. 2005. System and method for measuring stiffness in standing trees, US patent US6871545 Weyerhaeuser Company.

Chudnoff, M., Eslyn, W.E. and McKeever, D.B. 1984. Decay in mine timbers: Part III, Species-independent stress grading. Forest Products J., 34(3): 43-50.

Cown, D. 2005. Understanding and managing wood quality for improving product value in New Zealand. N. Z. J. For. Sci., 35 (2–3): 205-220.

Dadswell, H.E. and Wardrop, A.B. 1959. Growing trees with wood properties desirable for paper manufacture. Appita J., 12: 129-136.

Damodaran, T.K. and Chacko, K.C. 1999. Growth and wood characteristics of *Acacia mangium* gown in Kerala. Research report No. 174, Kerala Forest Research Institute, Peechi, India. 60p.

Dhanya, P. 2012. Destructive and non-destructive evaluation of wood properties in selected timbers in kerala. M.Sc. (Forestry) thesis, Kerala Agricultural University, Thrissur, 83p.

Dhanya, P., Anoop, E.V., Jayasree, C.E., Mohandas, A. and Chauhan, S.S. 2014. Destructive and non-destructive evaluation of seven hardwoods and analysis of data correlation. Holzforschung. 6p.

Dickson, R.L., Joe, B., Harris, P., Holtorf, S. and Wilkinson, C. 2004. Acoustic segregation of Australian-grown *Pinusradiata* logs for structural board production. Aust. Forestry, 67 (4): 261-266.

Dundar, T., Kurt, S., As, N. and Uysal, B. 2012. Non-destructive evaluation of wood strength using thermal conductivity, Wood Thermal Conductivity. BioResources. 7(3): 3306-3316.

Eckard, J.T. 2007.Rapid screening for solid wood quality traits in clones of loblolly pine (*Pinustaeda* l.) by indirect measurements. M.Sc thesis. Department of Forestry, North Carolina State University, Raleigh.

Gnanaharan, R. and Dhamodaran, T.K. 1992. Mechanical properties of rubberwood from a 35 year old plantation in Central Kerala, India. J. Trop. Forest Sci., 6(2): 136-140.

Greaves, B.L., Borralho, N.M.G., Raymond, C.A. and Farrington, A. 1996. Use of a Pilodyn for the indirect selection of basic density in *Eucalyptus nitens*. Canadian Journal of Forest Research, 26(9): 1643-1650.

Hansen, C.P. 2000. Application of the Pilodyn in Forest Tree Improvement. DFSC Series of Technical Notes. TN55, Danida Forest Seed Centre, Humlebaek, Denmark

Haygreen, G.J. and Bowyer, J.L. 1996. Forest products and wood science: an introduction (3rded). Ames: Iowa State University Press, 558p.

Henson, M., Boyton, S., Davies, M., Joe, B., Kangane, B., Murphy, T., Palmer, G., and Vanclay, J. 2004. Genetic parameters of wood properties in a 9 years old Eucalyptus dunnii progeny trial in NSW, Australia. *In* Proceedings of Eucalyptus in a Changing World, 11–15 October 2004, Aveiro, Portugal.

Hidayati, F., Ishiguri F., Iisuka K., Makino K., Takashima Y., Danarto, S., Winarni W.W., Irawati D., Naiem M. and Yokota S. 2013. Variation in tree growth characteristics, stress wave velocity, and pilodyn penetration of 24-year-old teak (*Techtonagrandis*) trees originating in 21 seed provenences planted in Indonatia. The Japan Wood Research Society.

Hildebrandt, G. 1960. The effect of growth conditions on the structure and properties of wood. 5th World Forestry Congress, 15th April, 1960. (eds. Culik, M and Passialis, C.K.) Seatle, Washington, 12p.

Ivkovic, M., Gapare, W.G., Abarquez, A., Ilic, J., Powell, M.B. and Wu, H.X. 2009. Prediction of wood stiffness, strength, and shrinkage in juvenile wood of radiata pine. Wood Sci. Technol., 43:237–257.

Jerome, C., Helene, C., Muller, L., Timothy, R.B., Tomas, A.E., Hanster, S. and Campbell, O.W. 2006. Regional and Phylogenetic Variation of Wood Density across 2456 Neotropical Tree species. Ecol. Appl., 16(6): 2356-2367.

Kabir, M.F., Schmoldt, D.L. and Schafer, M.E. 2002. Time domain ultrasonic signal characterization for defects in thin unsurfaced hardwood lumber. Wood and Fiber Sci., 34(1): 165-182.

Karlinasari, L., Wahyuna, M.E. and Nugroho, N. 2008. Non-destructive ultrasonic testing method for determining bending strength properties of Gmelina wood (*Gmelinaarborea*). J. Trop. Forest Sci., 20(2): 99–104.

Keogh, R.M. 1979. Does teak have a future in tropical America? Unasylva 31(126):13-19.

Keogh, R.M. 1996. Teak 2000: a consortium support for greatly increasing the contribution of quality tropical hardwood plantations to sustainable development. London, International Institute for Environment and Development (IIED.

Keogh, R.M. 2009. The future of teak and the high-grade tropical hardwood sector. FAO Planted Forests and Trees Working Paper Series FP/44, Rome. Available at http://www.fao.org/forestry/plantedforests/67508@170537/en/

Kien, N. D., Jansson, G., Harwood, C., Curt Almqvist, C. and Thinh, H. H. 2007. Genetic variation in wood basic density and pilodyn penetration and their relationships with growth, stems straightness and branch size for *Eucalyptus urophylla* S. T. Blake in Northern Vietnam. Research Centre for Forest Tree Improvement, Forest Science Institute of Vietnam. 20p.

Kjær, E.D., Lauridsen, E.B. &Wellendorf, H. 1995. Second evaluation of an international series of teak provenance trials. Humlebaek, Denmark, DANIDA Forest Seed Centre.

Kolin, B. 1988. Effect of moisture and temperature upon the compression strength parallel to the grain in the wood. Drvna Ind., 39(7-8): 165-175.

Kollert, W., Cherubini, L. (2012) Teak resources and market assessment 2010. FAO Planted Forests and Trees Working Paper. FP/47/E. Rome, Italy. http://www. fao.org/docrep/013/al464E/al464E.pdf

Kretschmann, D.E. and Green, D.W. 1996. Modeling moisture content mechanical property relationships for clear southern pine. Wood Fibre Sci., 28(3): 320-337.

Kube, P. and Raymond, C. 2002. Technical Report 92 Selection strategies for genetic improvement of basic density in *Eucalyptus nitens*byCooperative Research Centre for Sustainable Production Forestry August 2002.

Kubojima, Y., Okano, T. and Ohta, M. 2000. Bending strength and toughness of heat-treated wood. J. Wood Sci., 46 (1): 8-15.

Kumar, P., Ananthanarayana, A.K. and Sharma, S.N. 1987. Physical and mechanical properties of *Acacia auriculiformis* from Karnataka. Indian for., 113: 567-573.

Kumar, S., Jayawickrama, K.J.S. Lee, J. and Lausberg, M. 2002. Direct and indirect measures of stiffness and strength show high heritability in a wind-pollinated radiata pine progeny test in New Zealand, Silvae Genet., 51 (5–6): 256–261.

Lan, J. 2011. Genetic parameter estimates for growth and wood properties in Corymbiacitriodora subsp. variegata in Australia and Eucalyptus urophylla in China.

Lasserre, J.P., Mason, E.G. and Watt, W.S. 2007. Assessing corewood acoustic velocity modulus of elasticity with two impact based instruments in 11-year-old trees from a clonal spacing experiment of *Pinusradiata* D. Don. For. Ecol. Manage., 239: 217-221.

Launay, J., Ivkovich, M., Paques, L., Bastien, C., Higelin, P. and Rozenberg, P. 2002. Rapid measurement of trunk MOE on standing trees using rigidimeter. Ann. For. Sci., 59:465–469.

Lausberg, M.J.F., Gilchrist, K.F. and Skipwith, J.H. 1995. Wood properties of *Eucalyptus nitens* grown in New Zealand. N.Z.J. For. Sci., 25: 147-163.

Limaye, V.D. 1954. Grouping of Indian timbers and their properties, uses and suitability. Indian For. Rec. (Timb. Mech.)., 1(2): 19-67.

Lin, J.G., He, S.D. and Dong, J.W. 1999. Study on the variation pattern of basic density and mechanical properties of *Dendrocalamuslatiflorus* timber. J. Bamboo. Res., 18(1): 58-62.

Lindstrom, H., Harris, P. and Nakada, R. 2002. Methods for measuring stiffness of young trees. HolzRohWerkst., 60: 165-174.

Lindstrom, H., Harris, P. and Nakada, R. 2002. Methods for measuring stiffness of young trees. HolzRohWerkst., 60: 165-174.

Lohani, R.C. and Sharma, S.D. 2003. Some studies on the stiffness strength relationship in *Albizziaprocera* and *Prosopisjuliflora* for machine grading of timber. J. Timb. Dev. Assoc. India. 49(3) (3-4): 23-29.

Mochan, S., Moore, J. and Connolly, T. 2009. Using acoustic tools in forestry and wood supply chain. Forestry commission. FCTN018/FC-GB(ECD)/ALDR-1.5K/SEP09

Mochan, S., Moore, J. and Connolly, T. 2009. Using acoustic tools in forestry and wood supply chain. Forestry commission. FCTN018/FC-GB(ECD)/ALDR-1.5K/SEP09

Mochan, S., Moore, J. and Connolly, T. 2009. Using acoustic tools in forestry and wood supply chain. Forestry commission. FCTN018/FC-GB(ECD)/ALDR-1.5K/SEP09

Monteuuis, O., Goh, D.K.S., Garcia, C., Alloysius, D., Gidiman, J., Bacilieri, R., and Chaix, G. 2011. Genetic variation of growth and tree quality traits among 42 diverse genetic origins of Tectonagrandis planted under humid tropical conditions in Sabah, East Malaysia. Tree Genet. Genomes, 7: 1263–1275.

Muller, U., Stretenovic, A., Gindl, W. And Teischinger, A. 2004. Longitudinal shear properties of European larch wood related to cell wall structure. Wood Fibre Sci., 36(2):143-151.

Muneri, A. and Raymond, C.A. 2000. Genetic parameters and genotype-by-environment interactions for basic density, pilodyn penetration and stem diameter in *Eucalyptus globulus*. Forest Genet., 7(4): 317-328.

Oh, S.W. 1997. Relationship between compression strength parallel to grain and anatomical characters in *Pinusdensiflora*. J. Korean Wood Sci. Technol., 25(2): 27-32.

Parolin and Ferriera, L.V. 1998. Are these differences in wood specific gravities between trees in Varzea and Igapo (Central Amazonia)?.Ecotropica, 4: 25-32

Rajput, S.S., Lohani, R.C. and Shukla, N.K. 1998. Knots in conifers and their effect on bending strength. Van Vigyan, 36: 49-53.

Rajput, S.S., Shukla, N.K. and Khanduri, A.K. 1997. Studies on variation of specific gravity and compressive strength of different clones of *Populusdeltoides*. Van Vigyan, 35(3-4): 165-171.

Raymond, C. A. 2002. Genetics of Eucalyptus wood properties. Annals of Forest Science, 59(5-6), 525-531.

Raymond, C. A. and Muneri, A. 2001. Nondestructive sampling of *Eucalyptus globulus*and *E. nitens*for wood properties. I. Basic density. Wood Science and Technology. 35: 27-39.

Raymond, C.A. and Apiolaza, L.A. 2004. Incorporating wood quality and deployment traits in *Eucalyptus globulus* and *Eucalyptus nitens*. In: Walter, C. and Carson, M. (eds.), Plantation forest Biotechnology for the 21st Century, pp. 87– 99. ISBN: 81-7736-228-3

Raymond, C.A. and MacDonald, A.C. 1998. Where to shoot your pilodyn: within tree variation in basic density in plantation *Eucalyptus globulus*and*E. nitens*in Tasmania. New Forests,15:205–221.

Razali, A.K. and Hamami, S. 1993. Prospects and utilization. *Acacia mangium*: Growing and Utilization. (eds. Awing, A.K. and Taylor, D.). Winrock International and FAO, Bangkok, Thailand. pp. 225-241.

Rokeya, U.K., Hossain, M.A., Ali, M.R. and Paul, S.P. 2010. Physical and mechanical properties of (*Acaciaauriculiformis* × *A. mangium*) hybrid acacia. J. Bangladesh Acad. of Sci., 34(2): 181-187.

Sadegh, A.N. and Rakhshani, H. 2011. Mechanical properties of beech wood (*Fagus orientalis*Lipsky) naturally grown in north of Iran. Indian J. Sci. and Technol. 4(12): 1685 – 1686.

Santos PET, Geraldi IO, Garcia JN. 2004. Estimates of genetic parameters of wood traits for sawn timber production in Eucalyptus grandis. Genet. Mol. Biol. 27(4): 567-573.

Schniewind, A.P. 1989. Concise Encyclopedia of Wood and Wood Based Materials. Pergamon press, Headington Hill Hall, England, 354p.

Searles, G., & Moore, J. 2009. Measurement of Wood Stiffness in Standing Trees and Logs: Implications for End-Product Quality. COST E53–Bled, 21.

Sekhar, A.C. 1988. Physical properties of Indian timbers. In: Ranganathan, V., Bakshi, B.K., Purshotham, A., Krishnamoorthy, A. and Sekhar, A.C 9eds.). Handbook on Indian Woods and Wood Panels: Solid Woods. Oxford University Press, Delhi, pp. 70-93.

Sekhar, A.C. and Gulati, A.S. 1972. Suitability of Indian timbers for industrial and engineering uses. Indian Forest records No.2, 1-47.

Sekhar, A.C. and Negi, G.S. 1966. Variation of some mechanical properties along with the length of teak trees. Indian Forest Bulletin No. 251. Central Forestry Commission, Government of India, New Delhi, 256p.

Shanavas, A. and Kumar, B.M. 2006. Physical and mechanical properties of three agroforestry tree species from Kerala, India. J. Trop. Agric., 44 (1-2): 23-30.

Shepard, R.K. and Schottafer, J.E. 1992. Specific gravity and mechanical property-age relationships in red pine. Forest Products. J., 42: 60-66.

Shirin, F., Kumar, D. and Pederick, L. 1998. Variation in wood specific gravity of pinus radiate in Victoria, Australia. Indian for., 123(3): 150-157.

Shukla, N.K., Rajput, S.S. and Lal, M. 1988. Some studies on variation of strength properties from pith to periphery in eucalyptus hybrid. J. Indian Acad. Wood Sci., 19(1): 39-46.

Shukla, S.R., Rao, R.V., Sharma, S.K., Kumar, P., Sudheendra, R. and Shashikala, S. 2007. Physical and mechanical properties of plantation-grown *Acacia auriculiformis*of three different ages. Aust. For., 70(2): 86-92.

Soerianegara, I. dan R. H. M. J. Lemmens (editors). 1994. Plant Resources of South East Asia Timber Trees No. 5(1). : Major commercial Timbers Pudoc-Plo. Wagening Netherlands. Prakoso, K.U.

Sotelo Montes, C., Hernández, R. E., Beaulieu, J., & Weber, J. C. 2006. Genetic variation and correlations between growth and wood density of Calycophyllumspruceanum at an early age in the Peruvian Amazon. Silvaegenetica.

Sprague, J. R., Talbert, J. T., Jett, J. B. and Bryant, R. L. 1983. Utility of the pilodyn in selection for mature wood specific gravity in loblolly pine. Forest Sci., 29(4)1: 696-701.

Sretenovic, A.C., Muller, U., Gindl, W. And Teishinger, A. 2004. New shear assay for the simultaneous determination of shear strength and shear modulus in solid wood: finite elements modelling and experimental results. Wood Fibre Sci., 36(3): 302-310.

Stonecypher, R., Zobel, B.J. and Blair, R. 1973. Inheritance patterns of Loblolly Pines from a Non-selected Natural Population. North Carolina State University Agriculture Experiment Station. Technical Bulletin 220.

Subramanian KN, Nicodemus A, Radhamani A (1994). Teak improvement in India. For. Genet. Resour. 22:33-36.

Tewari, D.N. 1992. A monograph on teak (TectonagrandisLinn.f.). International Book Distributors, Dehra Dun, India.

Toulmin, M.J., Raymond, C.A. 2007. Developing a sampling strategy for measuring acoustic velocity in standing Pinusradiata using the TreeTap time of flight tool. N. Z. J. For. Sci. 37: 96-111.

Valente, C.A., de Sousa, M.A., Furtado, F.P. and de Carvalho, A.P. 1992. Improvement program for *Eucalyptus globules* at Portucel: Technological component. Appita. J., 45: 403-407.

Walker, J.C.F. 1993. Primary wood processing – principles and practices. Chapman and Hall publication, London, 612p.

Wang, X., Ross, R.J., McClellan, M., Barbour, R.J., Erickson, J.R., Forsman, J.W. and McGinnis, G.D. 2000. Strength and stiffness assessment of standing trees using a non-destructive stress wave technique. Research Paper, Forest Products Laboratory, USDA Forest Service (FPL-RP-585), 9 pp.

Wang, X., Ross, R.J., McClellan, M., Barbour, R.J., Erickson, J.R., Forsman, J.W. and McGinnis, G.D. 2001. Non-destructive evaluation of standing trees with a stress wave method. Wood Fiber Sci., 33(4): 522-533.

Wei, X., &Borralho, N. M. G. 1997. Genetic control of wood basic density and bark thickness and their relationships with growth traits of Eucalyptus urophylla in south east China. Silvaegenetica, 46(4), 245-249.

Wessels, C.B., Malan, F.S. and Rypstra, T. 2011. A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber. Eur. J. Forest Res., 130:881–893.

Williams, R.F. and Hamilton, J.R. 1961. The effect of fertilization on four wood properties of slash pine. J. For., 59: 662-665.

Wimmer, R., Downes, G.M., Evans, R., Rasmussen, G. and French, J. 2002. Direct effects of wood characteristics on pulp and paper hand sheet properties of Eucalyptus globules. Holzforschung, 56: 244-252.

Wu, S., Xu J., Li, G., Vuokko, R., Lu Z., Li, B. and Wei, W. 2011. Estimation of basic density and modulus of elasticity of eucalypt clones in southern china using non-destructive methods. J. Trop. Forest Sci., 23(1): 51–56.

Yao, J. 1968. Modified mercury immersion method in determining specific gravity of small, irregular specimens. For. Prod. J., 18(2): 56–59.

Yoshihara, H. and Satoh, T. 2003. Examination of the off axis tension test method for evaluating the shear properties of wood. Forest Products J., 53(5): 75-79.

Zobel, B. & Van Buijtenen, J.P. (1989). Wood variation: its causes and control. Springer-Verlag Heidelberg, 363 p.

Zobel, B.J. & Jett, J.B. (1995). Genetics of wood production. Springer-Verlag New York, 352 p.

Zobel, B.J. and Talbert, J. 1984 Applied Forest Tree Improvement. John Wiley & Sons Inc. New York, 505 p.

Zobel, B.J. and van Buijtenen, J.P. 1989. Wood variation: its causes and control. Springer-Verlag, Berlin, Germany, 363p.

Zobel, B.J., Thorbjornsen, E. and Henson, F. 1960. Geographic site and individual tree variation in wood properties of loblolly pine Silvae Genet 9. pp 149-158.

GENETIC VARIATION IN WOOD BASIC DENSITY AND MOE AND THEIR RELATIONSHIP WITH GROWTH TRAITS IN TEAK (*TECTONA GRANDIS* L. F.) GROWN IN SEED ORCHARDS OF KERALA

By

JILJITH, K.P.

ABSTRACT

Master of Science in Forestry

Faculty of Forestry

Kerala Agricultural University

DEPARTMENT OF WOOD SCIENCE

COLLEGE OF FORESTRY

KERALA AGRICULTURAL UNIVERSITY

VELLANIKKARA, THRISSUR -680 656

KERALA, INDIA

2016

ABSTRACT

A study on the variation in wood basic density and dynamic modulus of elasticity of teak (*Tectona grandis* L.f.) trees grown in tree improvement trials at various locations in Kerala using destructive and nondestructive testing (NDT) methods was conducted in the College of Forestry, KAU, Vellanikkara, Thrissur during the period 2012-2015. The investigation focused on the variation in physical and mechanical wood properties of teak, and to understand their relationship with growth traits and evaluating the suitability of NDT methods as predictors of timber properties under field conditions.

Pilodyn (6J) and Treesonic Microsecond Timer (FAKOPP) were the two NDT equipments used in the study. Teak logs collected from a forest plantation (Elival, Palakkad) were destructively analysed following nondestructive testing with the above equipments. Discs and logs were analysed for within tree variation in Pilodyn pin penetration depth (PPD) and were further subjected to various mechanical tests using UTM as well. Significant variation in mechanical properties, and Stress Wave Velocity (SWV) was observed between the trees sampled. Most of the mechanical properties assessed destructively were found to be highly correlated with SWV. PPD in the periphery of the trees was related to the same in the middle portion of the trees. Pilodyn readings also correlated well with the actual wood basic density analysed destructively. In general, both the NDT instruments were found to be useful in estimation of the respective properties using regression analysis.

In standing trees of a CSO (Walayar, Palakkad), an SPA (Nilambur) and two clonal trials (Chettikkulam and Vellikulangara, Thrissur) non-destructive evaluation was repeated. The study revealed high genetic divergence in the wood traits and indicated greater scope for application in tree improvement trials. Growth traits didn’t show any consistency or trend with the differing age of the plantations, nor any convincing relationship with the wood traits. Clusters were also identified for the clones at Walayar and Chettikkulam based on which selection for further breeding programmes can be undertaken.